(continued from part 12)

The capacitor as analogue memory

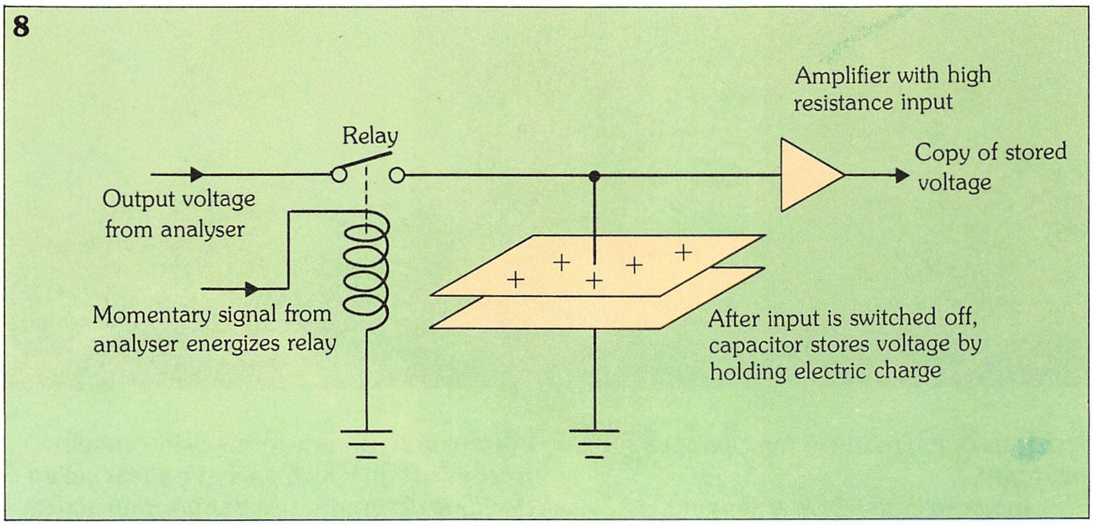
A gas analyser samples its gas mixture every 15 minutes, registering the quantities of the three constituent gases as a percentage of the total. Each quantity appears as a voltage analogue signal at the analyser output for a few seconds only. As the three (in this case) voltage signals are produced one at a time over an interval of 15 minutes, *a three-channel analogue storage buffer* is required to **store** the voltage signals until the analysis is complete. All three signals can then be transmitted, via an interface, to the computer for recording.

Figure 8 illustrates the principle behind one of the three voltage storing channels. As soon as a new voltage is registered, the analyser energises the electromagnet in a **relay** for a short time. The magnetic field attracts a metal arm and closes the relay contacts, connecting the voltage output to the capacitor for a few seconds. Current then flows between the analyser output and the capacitor, resulting in an accumulation of charge on the capacitor plates at a voltage equal to that of the analyser output.

Capacitors, which comprise two closely spaced metal plates separated by a thin insulating layer preventing current flow between them, serve many different functions in electrical circuits. In this example, the capacitor acts as a *storage reservoir for electric charge.* The more charge that is fed into the capacitor, indicated in *figure 8* by the plus signs, the higher the voltage that is stored. When the capacitor has been charged to the voltage level of the analyser output, the relay contacts are opened, disconnecting the capacitor. The input voltage is then stored until the relay is closed again, allowing the next output voltage from the analyser to flow into the capacitor.

The important task of 'reading' the stored voltage, without changing it too much, and sending a close copy to the computer interface, is performed by a special amplifier circuit. Like all amplifiers, its circuit symbol is a triangle.

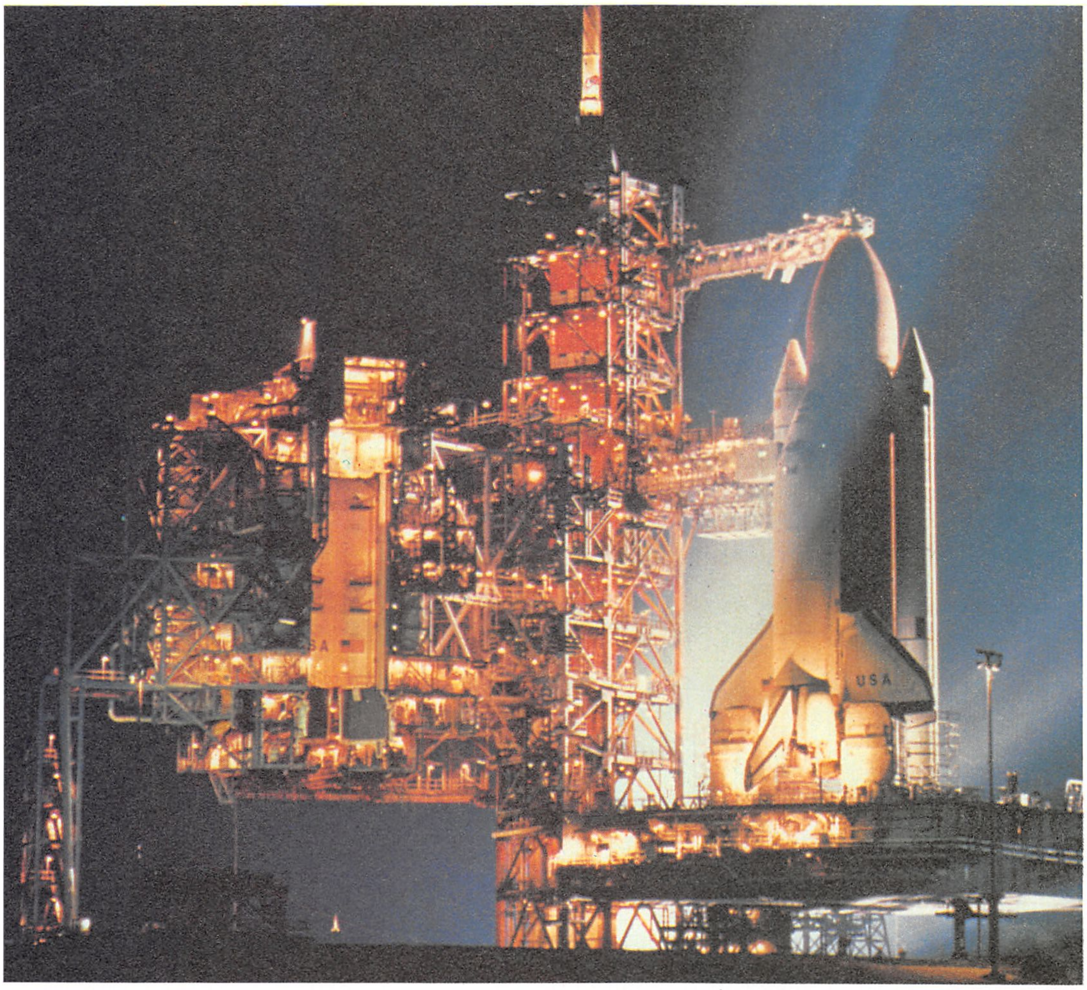
Although the amplifier has a very high resistance in its input, a small amount of charge will **drain** from the capacitor, lowering the voltage stored across its plates. Over the storage period of 15 minutes, the amplifier output voltage will **decay** gradually from the initial, correct, value. The decay of stored voltage across a capacitor can therefore introduce significant error in applications where accuracy is important. However, as we said earlier, this is about the only practical method of storing analogue information for longer than a fraction of a second. Storage then, constitutes a major problem when using analogue systems.



8. One of the three voltage analogue signals from the gas analyser being stored in the capacitor.

How do analogue circuits make decisions?

We have seen how analogue circuits store information, but how do they make decisions? We have already seen analogue



The Research House/NASA

Left: without digital technology, the space programme would not have been possible.

decisions being made in our previous examples.

In *figure 2*, the float and variable resistor in the petrol gauge determine what current to transmit in response to a certain petrol level. This process can be considered as a sort of decision. The meter, in turn, decides what level to indicate for a certain current. Similar decisions are made by the microphone element and the earpiece in the telephone system in *figure 3*.

In the AM radio transmitter of *figure 4*, the modulator performs a *voltage multiplication* decision: the modulator continually multiplies the input voltage by a factor controlled by the gain signal provided by the microphone.

From these examples we can take a general rule that whenever electricity is modified in some way in an analogue circuit, information is being processed. Existing information is used to create new information, or new forms of information. It is this action which we have so far called *deciding*, to emphasise its importance with regard to information.

An important point to note is that the analogue decisional process is not composed of separate steps, as in a digital system, but is a *continuous process*. When electronic components such as transistors are involved, say, in an amplifier, the components do not switch on and off; instead, they vary the flow of current between the on/off states in a smooth or analogue fashion.

A transistor operating in this inbetween range acts as an electrically controlled variable resistor **amplifying element**: a *small* change in the control signal varies the effective resistance of the transistor, producing a *large* or **amplified** change in output signal. Transistor amplifiers – of various kinds – are the main building blocks in electronic analogue systems.

Advantages of digital systems

In order to understand why digital techniques are preferred in some applications, we'll now make some direct comparisons between digital and analogue methods. *Table 1* lists the advantages and limitations to be considered.

Digital systems are easier to design

As we have already noted in analysing and designing digital systems, the only immediate concern with electricity is whether it is *on* or *off*. The *exact* voltage or current in a wire is irrelevant: it just must not be inbetween the two permitted states. As a result, the switching circuits used are considerably more simple than analogue circuits, and their components don't have to fit such narrow specifications.

Furthermore, digital systems are built from a few simple circuits, such as gates and flip-flops, and the larger building blocks (decoders, counters, etc.) are made up from these. Also, within any given digital system, the gates and flip-flops are usually from a single family of digital circuits – TTL, CMOS, I^2L etc. – meaning that they closely resemble one another. Consequently, these building blocks are all perfectly **compatible**, provided the system designer follows the few simple rules that we've discussed. Digital designers can, in effect, build systems to specific designs, much like assembling Lego kits.

Table 1
Advantages and limitations of digital systems

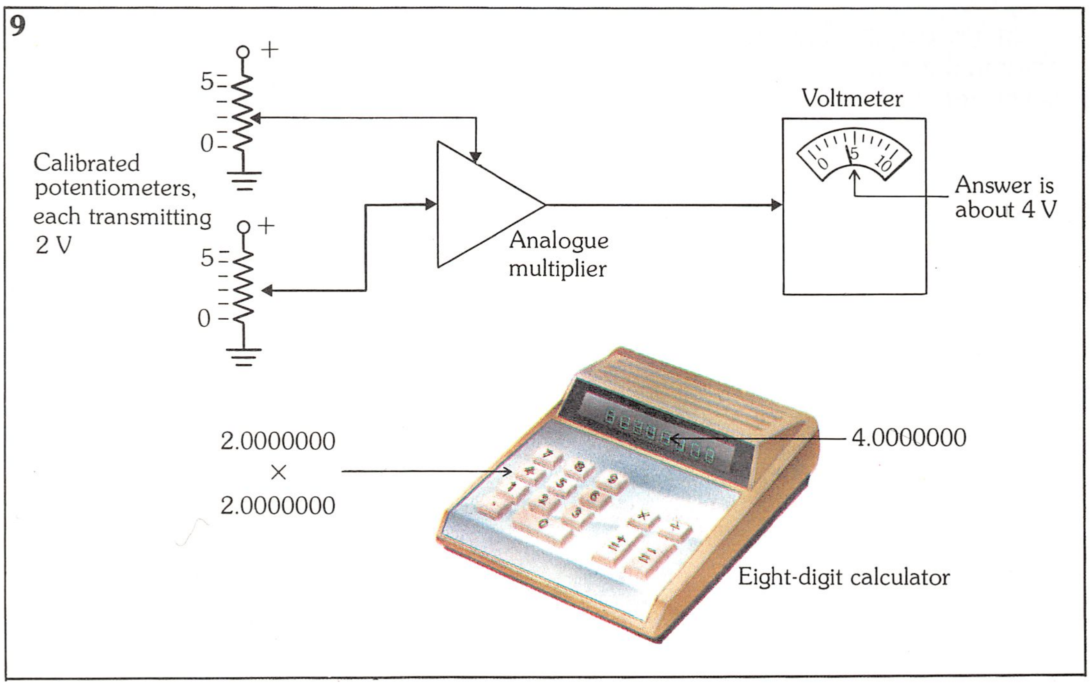
Advantages	Limitations
• Easier to design • Accuracy • Storage is simple • Faster • High level of integration	• Real world is analogue • Analogue is simpler • Slower transmission

Digital processing is accurate

Analogue systems rely on producing a copy of the original information. However, as we have seen, this copy is never an exact representation – a degree of **error** will always be present which is expensive and difficult to eliminate.

For example, using an amplifier, it is possible to multiply two by two: the amplifier might have a gain of two and a voltage of 2 V could be applied at the amplifier input. Because of analogue errors, the amplifier output voltage is not likely to be *exactly* 4 V, but more like 3.976 V or 4.028 V, depending on the

9. Comparing digital and analogue multiplication illustrates that digital techniques are more accurate.



degree of accuracy of the amplifier (see *figure 9*). You can see why analogue methods are not used for handling precise information.

Digital processing, on the other hand, produces highly accurate results. The pocket calculator looked at earlier handles eight digit decimal numbers, so we can multiply 2.0000000 times 2.0000000 and obtain the result 4.0000000.

Large computers can manipulate numbers with many more digits, and consequently are much more accurate. The cost of this extra precision in a digital system is much less than it would be in a comparable analogue system because the same digital building block circuits are used – just more of them, for more digits.

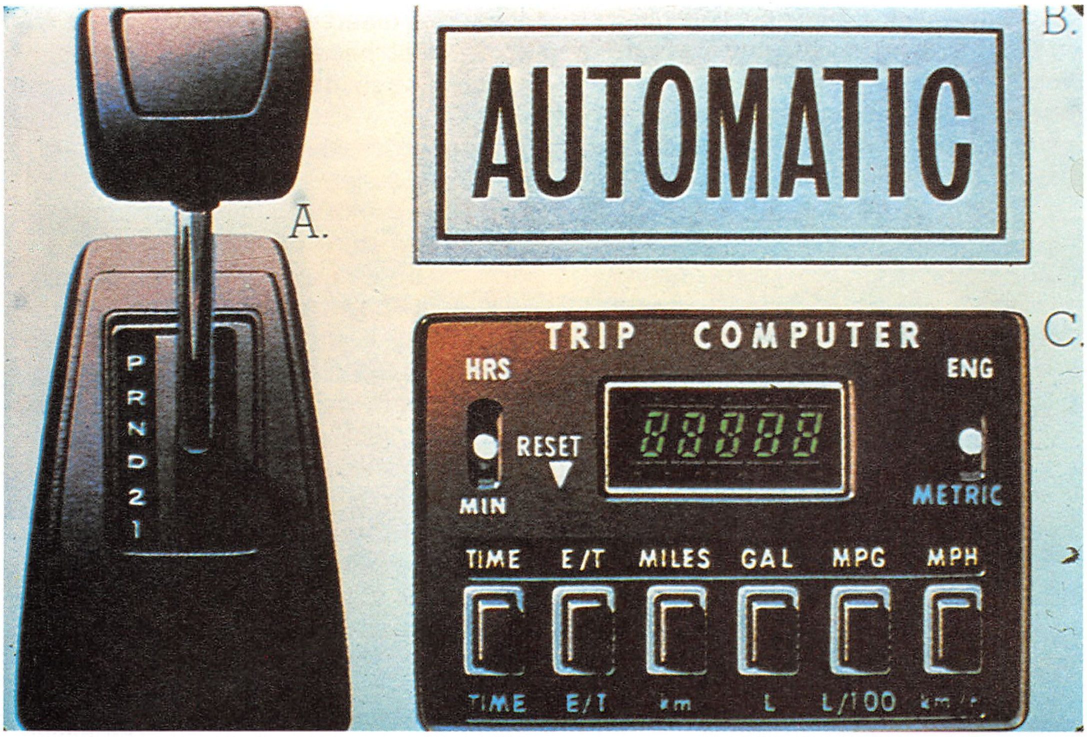
Digital storage is simple
As we have seen with the capacitor storage system of *figure 8*, storing analogue information can never be perfectly accurate. Switching circuits, however, like the flip-flop, can latch onto an item of digital information and hold it accurately for as long as needed.

If long-term, accurate information storage is needed in an analogue system, the information has to be converted into digital form and then stored using digital techniques.

Digital methods can be faster
Analogue information handling can take a considerable time. The problem is usually inherent within the system and depends on what types of components are used. If for any reason high-value capacitors (as in analogue storage) or **inductors** are used, then this time factor will be an important consideration. (An inductor is any device which makes the electric current interact with a magnetic field – any component with a coil of wire is an inductor, e.g. the ammeter in *figure 2* or the telephone earpiece in *figure 3*.) For example, approximately one second would be needed to build up the charge in a capacitor used in analogue memory (like that in *figure 8*); by comparison, flip-flops will store an equivalent digital input data item in only a few nanoseconds.

Higher levels of integration are possible
The most important advantage of digital systems is the level to which digital circuits can be integrated into single ICs.

Benefits such as simplicity, accuracy, storage and speed were inherent in the



Left: a 'trip computer' from a vehicle which uses a TMS 1000 4-bit microcomputer.

digital concept and contributed to the growth of digital techniques in computers etc. These benefits also influenced some secondary applications in otherwise analogue systems, such as storage, or in switching analogue signals, for example, a telephone exchange.

But the biggest boost to digital technology came with the introduction of integrated circuits. Digital circuits are much easier to integrate than analogue circuits. It only takes a brief look at some modern microprocessor and microcomputer ICs to see the effect of high levels of integration. ICs are now being manufactured with many thousands of gates and flip-flops on single chips, and greater levels of integration are limited only by the accuracy with which the chips can be designed.

Why haven't analogue circuits been integrated to the same sort of level? There are two main reasons. First, some analogue components, inductors, transformers and high-value capacitors, cannot be made in an integrated form, or at least not in an economical way.

Second, all digital systems, however large and complex, are built from the two basic building blocks – gates and flip-flops. Analogue circuits, on the other hand, have *many* forms of basic building blocks, each one different and not interchangeable.

Below: analogue and digital systems work very well side-by-side, as in this electronic navigation system.

Many types of analogue ICs may therefore be required in a particular analogue system; no single analogue IC would be capable of performing the range of tasks that a single digital IC can perform. Nevertheless, progress has been made in the design and manufacture of analogue ICs.

The most widespread analogue IC is the **operational amplifier** (OPAMP). This is an important building block in analogue systems and can be made to perform practically any kind of amplification with the addition of a few chosen resistors and capacitors. Operational amplifiers are known as **differential amplifiers** which means that they amplify the voltage difference between the two inputs; output voltage can be as much as 100,000 times this difference. This enormous **voltage gain** is reduced to any desired value by a technique known as **negative feedback**, in which part of the output voltage is routed back to one of the inputs.

An operational amplifier always has a limited range of frequencies which may be amplified, called a **bandwidth**. Without negative feedback, this bandwidth is usually very small – in modern OPAMPs it is artificially limited to 0-15 or 20 Hz in order to keep the amplifier stable. With negative feedback, the bandwidth may be as high as 1 MHz. This bandwidth is dependent upon the type of operational amplifier and also, to a large extent, on the circuit of which it is a part. Above the **cut-off frequency** of 1 MHz, the voltage gain drops sharply.

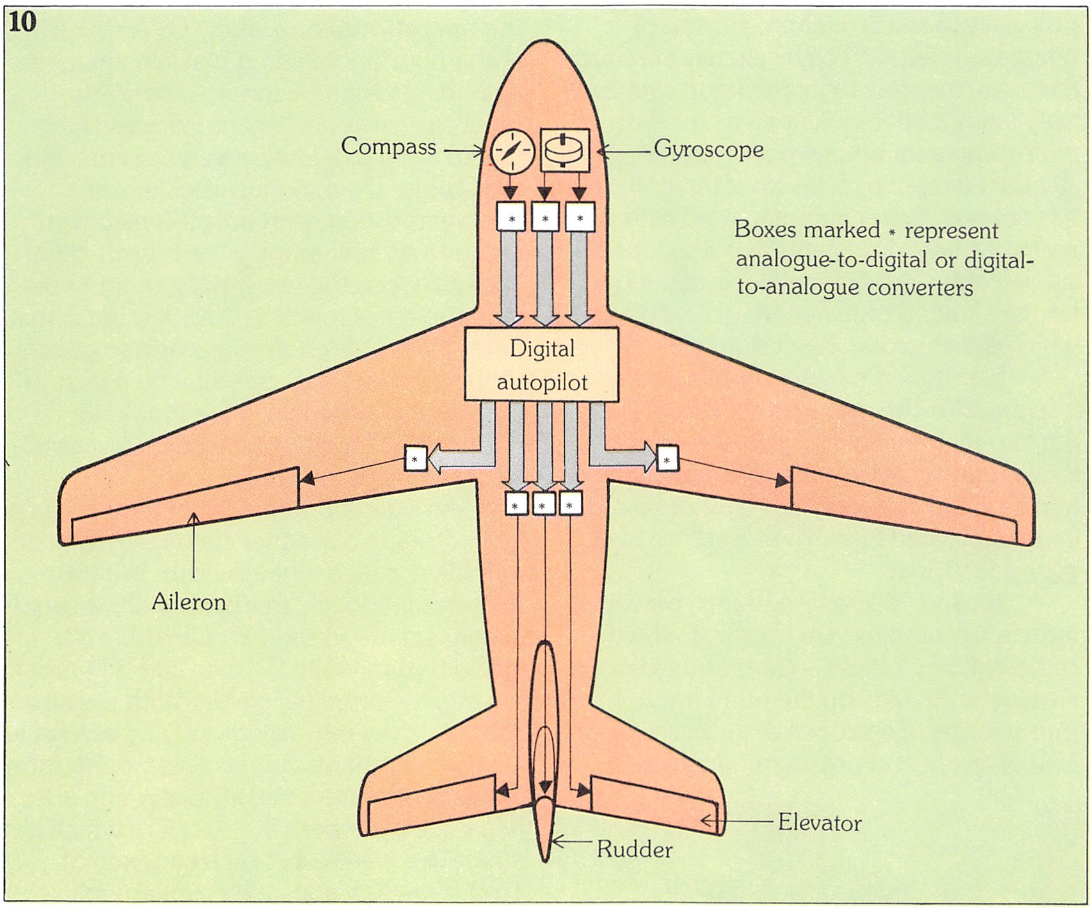
Some types of operational amplifier, known as **broadband amplifiers**, can be used for frequencies much higher than this, say, 500 MHz. Generally, gain is controlled in such ICs by a control voltage rather than by negative feedback. These ICs are ideal for use in TV or radio tuners.

Although the problem of heat dissipation from ICs is a considerable limitation to the amount of current which can pass through the chip, there are some types of **power** operational amplifier which provide up to about 20 W of power output. With a single such analogue IC and a few resistors and capacitors, a small but appreciably loud hi-fi amplifier can be made.

To sum up, you can see that analogue ICs are used as the central parts of various specialised analogue systems.

Digital limitations

Surprising as it may seem, digital techniques do have intrinsic limitations which exclude their use in certain applications. *Table 1* lists the limitations that we'll now examine.



10. The automatic pilot system of an aircraft converts analogue information from the real world into digital form for processing. It is then reconverted back to analogue output supplying information controlling the rudder, ailerons etc.

The real world is analogue

The first and most important point to consider is that the information which enters and leaves a system is, by its very nature, of analogue form. The systems that we have looked at have all processed analogue information (petrol level, instrument readings, sound, radio waves). In practice, most natural information – temperature, pressure, weight, intensity, position, time, speed and so on – is analogue. Although we are used to expressing this type of information in digital form – your weight might be 66.379 kg for example – we are actually stating a digital approximation for an analogue quantity.

When a digital system handles analogue information from the *real world*, it must first be converted into digital form; the digital output is then converted back to analogue form after processing. An example of such a digital system, the automatic pilot system of an aircraft, is shown in *figure 10*. The system is fed information about the aircraft's direction from the compass, and inclination from the gyroscope. As a result of this input, the autopilot supplies analogue output information controlling the rudder, ailerons and elevator which keep the aircraft on the required course and at the prescribed altitude.

Such two-way conversion of analogue to digital information can be complicated and hence expensive. On top of this, the conversion process inevitably introduces inaccuracies and takes finite time, both of which may be critical. In the case of the autopilot, the advantages offered by digital processing outweigh the cost and complexity of analogue–to–digital and digital–to–analogue conversion. We shall now look at a system where it is, perhaps,

preferable to process the information in an analogue way.

Analogue processing is simpler

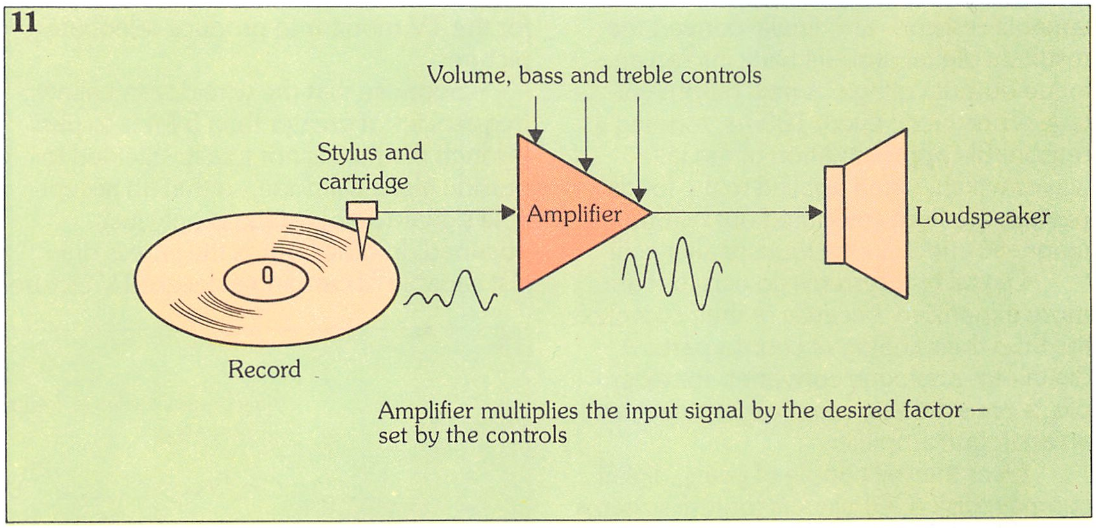
Suppose we are designing a system which has analogue inputs and outputs, but the processing part of the system is as yet undefined. What is the basis for the decision to process the analogue information in analogue or digital form?

Take as an example your home hi-fi system. The majority of such systems process the tiny analogue signals from the stylus and cartridge of the pick-up arm. The cartridge acts as a transducer, converting the minute movements of the stylus, as it traverses the record groove, into electrical analogue information.

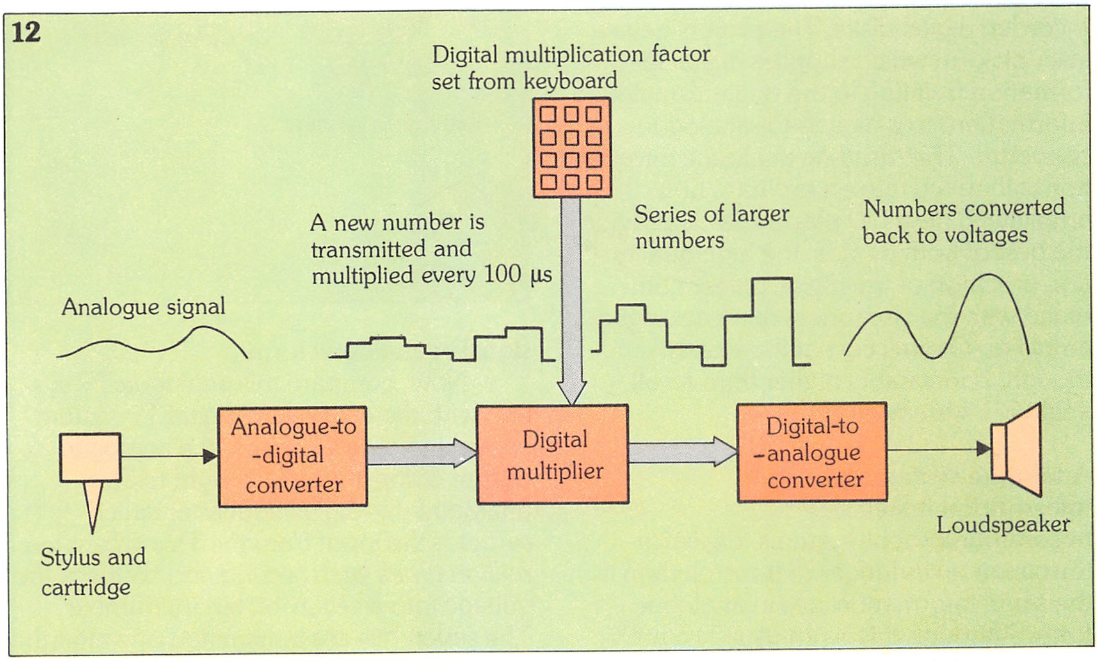
The system's main task is simply to multiply the amplitude of this information by a factor depending on the volume, treble and bass control settings, to produce a proportionally taller and more powerful copy of this information to drive the loudspeaker. *Figure 11* shows the principle of such an analogue system.

Magnification, as we saw earlier, can be accomplished with sufficient accuracy by a single analogue amplifier (or an IC power amplifier). Even though this system uses a complex hi-fi amplifier, it is still simpler than a comparable digital system

11. Amplification of analogue signals (from a hi-fi, for example) is an example of a task more economically performed by analogue circuitry.



12. The equivalent digital system to that shown in figure 11.



(*figure 12*). The digital system needs to regularly check the input signal from the cartridge (every 100 μs or so); convert each voltage to a corresponding binary number; multiply the number by a digital volume control factor (entered, say, from the keyboard as shown – to avoid having to convert the analogue signal from a variable resistor); and finally convert the resultant digital product back into an analogue output voltage. A new output voltage is produced every 100 μs, forming a reasonable approximation of the taller waves which, when applied to the loudspeaker, are then smoothed out by the magnetic effects in the loudspeaker coil.

Digital hi-fi systems do exist but are more expensive, because of their complexity, than their analogue counterparts. A digital–to–analogue converter, for example, is considerably more expensive than an analogue amplifier.

Over the last couple of years, digital compact disk (CD) players for hi-fi systems have been introduced, these use specially recorded digital disks. The players have a laser pick-up which supplies digital information (relating to the original analogue information) to a digital–to–analogue converter. The resulting analogue information is then fed into an ordinary hi-fi amplifier. These CD players really provide the best of both worlds: the high quality and precision of the digital player combined with the cheapness of an analogue amplifier. Overall cost of the system though, is inevitably higher than an all analogue system.

Analogue systems transmit information faster

In communications systems, digitial information takes longer to transmit than if the same information was in analogue form. Although this is not usually a problem, it does become evident when the capacity of the transmission system is pushed to its limit.

Figure 13 shows a remote TV camera which transmits a voltage analogue television signal to a TV monitor. Let's assume that the capabilities of the system are limited only by the wire between the camera and TV.

Signals from the camera can vary in frequency between 0 Hz and 5 MHz. The TV monitor can produce adequate pictures if the electrical noise present in the received signal is no greater than 1/128 th of the full range of voltage. A communications engineer would say that a bandwidth of 5 MHz, and a **signal-to-noise ratio** of 42 decibels (abbreviated 42 dB) is required for the TV monitor to produce adequate pictures.

Suppose that the wire doesn't allow frequencies of greater than 5 MHz to pass through it, and it is not totally shielded to outside electrical noise, so that an acceptable signal-io-noise ratio is only just obtained. In other words the wire is only just capable of carrying a decent TV picture signal in analogue form.

13. An example of an analogue transmission system operating satisfactorily at the limits of frequency and accuracy capability.

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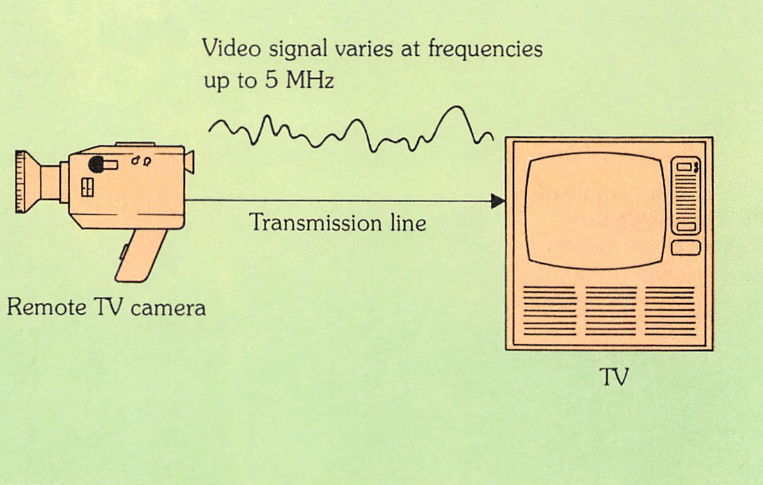
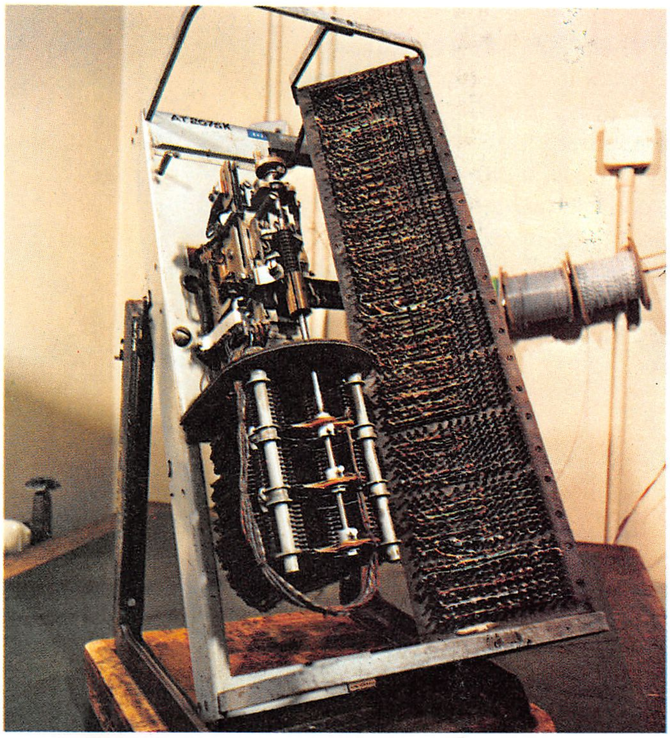
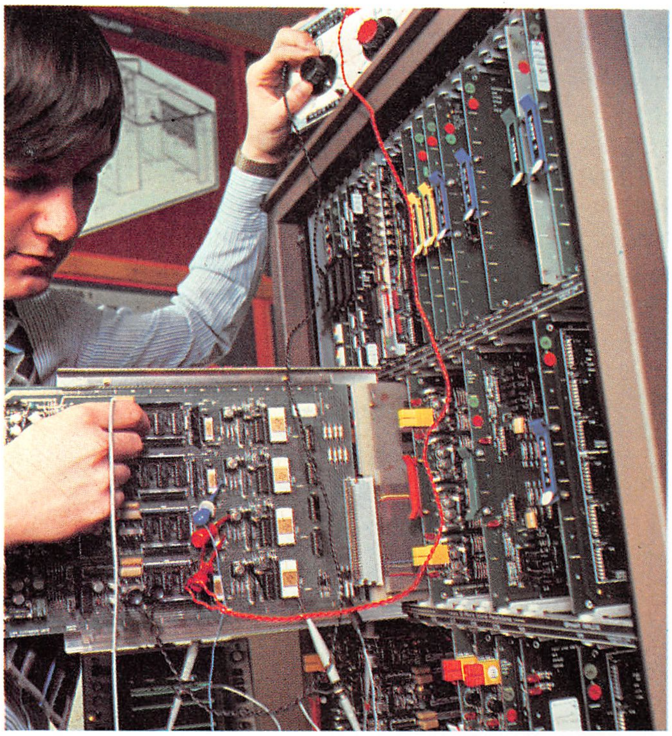


Now, compare this analogue TV system with the equivalent digital TV system shown in *figure 14*. Here, the analogue output of the TV goes straight to an analogue–to–digital converter which samples the input from the TV camera *ten million times each second* and converts the voltage into a seven-bit binary number. The seven bits are transmitted one after the other down the wire in serial fashion. So the total number of bits per second transmitted down the wire will need to be 70 million, i.e. at a frequency of 70 MHz.

At the other end of the wire, the digital–to–analogue converter reconverts the digital signal to the analogue voltage signal which the TV needs.

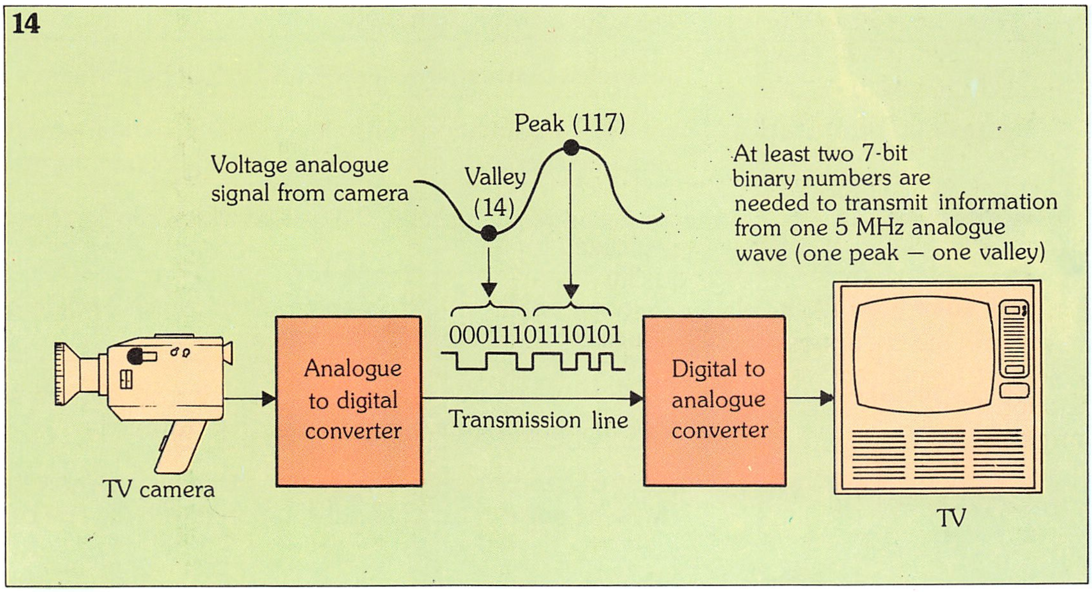
The point to note in this example is that a digital signal with a frequency of 70





The Research House/British Telecom

Above: an example of the old analogue switching circuitry in a telephone exchange (on the left) which is being replaced by digital circuits (on the right). One of these boards now replaces a considerable number of the old analogue mechanisms.



14. Equivalent digital system to the analogue T.V. system shown in figure 13. Note that a frequency of 70 MHz is required to transmit TV pictures of the same quality and accuracy as the 5 MHz analogue system.

MHz is required to transmit TV pictures of the same quality and accuracy as the 5 MHz analogue signal. The waveform shown in *figure 14* illustrates why this is so: ten million numbers per second means that not only the *peak* of each 5 MHz analogue wave can be measured but also the *valley* next to it – *both* measurements are needed in order to reconstruct the signal at the receiving end. Also, seven bits per number allows a range from zero (0000000) to 127 (1111111) – so each measurement is accurate to within 1/128th of the voltage range, giving the required signal-to-noise ratio of 42 dB.

Remember, the original transmission wire used between camera and TV only has a bandwidth of 5 MHz. It cannot handle the equivalent 70 MHz digital signal. The signal would lose amplitude as it passes through the wire and will not be recognised at the receiving end.

This explanation of why digital transmission is slower than analogue transmis-

sion is highly simplified. But the general principles you've seen apply to any **transmission channel** that can carry either digital or analogue information, for example, telephone wires, radio broadcasts, and microwave radio links. As we said, problems with the speed or bandwidth of digital transmissions only arise when a transmission system is pushed to the limits of its capacity. In such a case, the problems can preclude any possibility of using digital transmission methods.

Even so, there can be an advantage to the use of digital transmission. Suppose that you have a noisy transmission channel, i.e. it has a low signal-to-noise ratio, but it has no limit to its bandwidth. Analogue signals can be transmitted accurately and noise-free if they are in digital form.

The method used, therefore, digital or analogue, depends on the application and the price you want to pay.

Glossary

ammeter	a meter which measures current in an electric circuit
amplitude modulation	form of analogue information transmission in which the amplitude of a high frequency carrier is modulated, i.e. varied, by the analogue information
bandwidth	frequency range of part or whole of an analogue system
decay	the fall of voltage across a capacitor as the charge stored in the capacitor is slowly removed
error	difference between the desired and actual performance of a system
frequency modulation	analogue information transmission in which the frequency of a high frequency carrier is modulated by the analogue information
modulator	special amplifying circuit, the gain of which can be controlled by a voltage
negative feedback	use of part of the output of an amplifier routed back to one of the inputs to control the amplifier's gain
operational amplifier	analogue integrated circuit which, with the addition of only a few chosen components, can form a working amplifier
signal-to-noise ratio	rating of a transmission channel (in dB) which defines the size of electrical noise in the channel compared with the size of signal

Transistor amplifiers

12 SOLID STATE ELECTRONICS

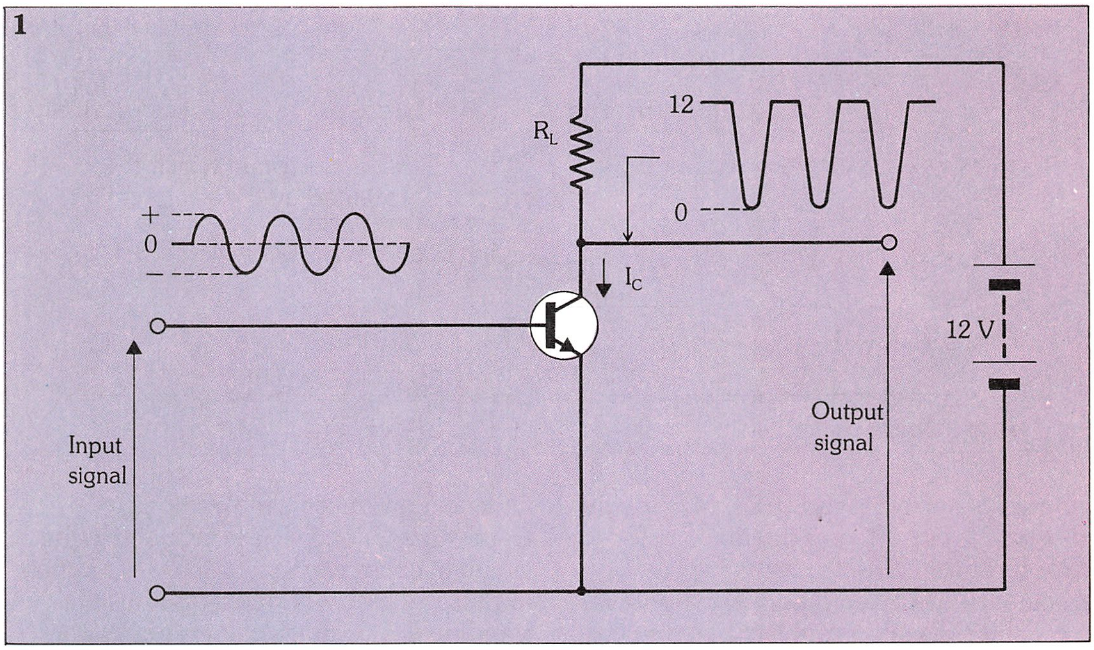
Common emitter amplifiers

In previous *Solid State* chapters, we looked at how transistors provide current amplification, and the different ways of connecting them to do so. Bearing this in mind, we shall now examine the way a transistor is used in simple amplifying circuits. We shall concentrate on the common emitter configuration as it is perhaps the most widely used, however the general concepts also apply to common base and common collector circuits.

We already know that transistors have an operating range, in which output varies with respect to input and it is this phenomenon which is employed in transistor amplifying circuits. It should be remembered, however, that the situation isn't quite as simple as applying an input signal and obtaining an amplified output signal. The circuit shown in *figure 1* explains why this is so. The input signal, applied between the transistor's base and emitter, is shown as a waveform and is seen to be an AC signal alternating about 0 V: first in a positive half-cycle, then in a negative half-cycle. Resistor R_L is the load resistor, used to convert the output current of the transistor, the collector current, to an output voltage. (Remember from Ohm's law, V = IR: so any change in the current through the resistor creates a change in the voltage across the resistor.)

When the input signal is at 0 V (before it has started to alternate in a positive direction) it is below the threshold voltage of the base-emitter p-n junction and the transistor is off, i.e., it acts as a high resistance and no collector current flows. The output voltage is therefore at its maximum value of about 12 V.

As the applied input signal begins to alternate in a positive direction it increases above the base-emitter threshold voltage, and base current flows into the transistor:



1. Circuit showing distorted output due to the transistor being non-biased.

the transistor then begins to turn on and its resistance decreases. Collector current starts to flow through the load resistor (a little at first, but increasing as the voltage at the input increases) and so the output voltage begins to fall. As the input voltage moves through its maximum voltage and then drops to 0 V, so the output voltage reaches its minimum value and then increases back to 12 V – the transistor is once more turned off.

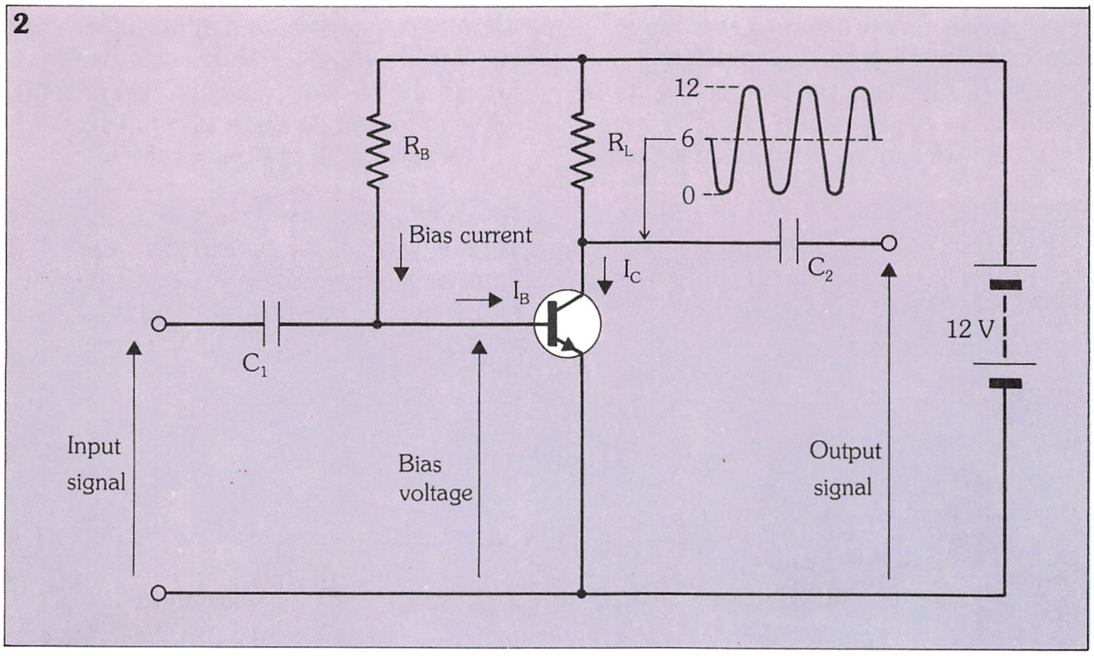
But what happens during the negative half-cycle of the input voltage? The transistor is always turned off because the base-emitter p-n junction is reverse-biased, so no collector current flows and the output voltage remains at 12 V. We say the transistor is **cut-off**, or is operating in its **cut-off region**. This produces the highly irregular or **distorted** output signal shown.

This presents a problem because the same thing happens whatever alternating signal is applied to the input. The solution, however, is simple. Considering only the standing direct voltages within the circuit, we see that if a fixed base current which is large enough to turn the transistor permanently half on is applied to the transistor, then the standing output voltage will be half way between 12 V and 0 V, i.e. 6 V. If an AC input signal is then applied, its positive half-cycles will produce corresponding negative half-cycles (between 6 V and 0 V) in the output voltage; and the input negative half-cycles will produce corresponding *positive half-cycles in the output voltage* (between 6 V and 12 V). This eliminates the distortion producing a true linear AC transistor amplifier. Such a circuit is shown in *figure 2*. The permanent base current is taken from the 12 V power supply and is fixed in value by the resistor R_B.

Applying a fixed base current to the transistor in this way is known as **fixed biasing** or **base current biasing**, and resistor R_B in *figure 2* is termed a **bias resistor**. The fixed base current is called a **bias current** and the fixed base-emitter voltage it produces is a **bias voltage**. Capacitors C_1 and C_2 are included in the circuit because capacitors allow AC signals to pass but block DC voltages, thus the standing DC voltages of any circuits preceding or following do not affect the DC voltages within this circuit. These DC voltages are sometimes called the **large-signal** or **steady-state** condition and the AC voltages, **small-signals**.

We now have a basic circuit which can be used to form an AC amplifier – how do we decide what value of biasing components to use? In effect, how do we design the circuit?

First we need to determine which type of transistor best suits the application.



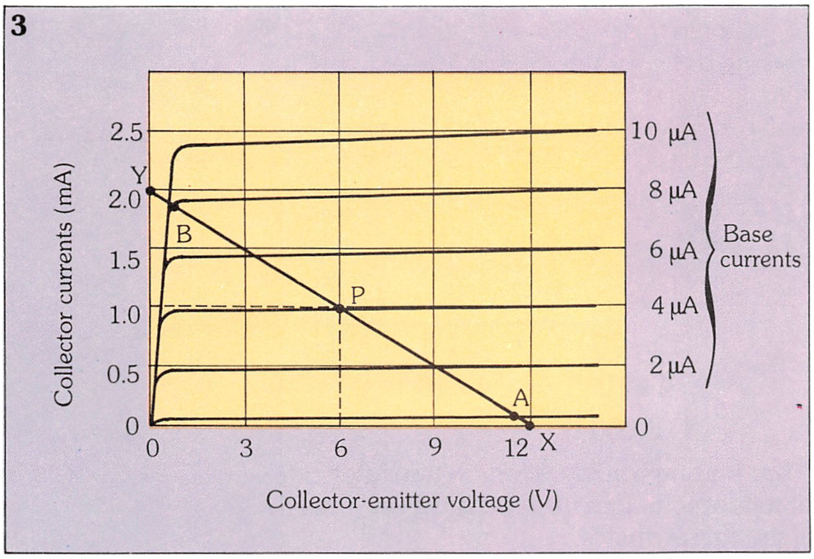
2. A true AC transistor amplifying circuit.

As we saw in *Solid State 11*, the information obtained in the characteristics and data sheets supplied by manufacturers enables us to do this. All examples here relate to a single n-p-n transistor; the methods and descriptions used also apply to p-n-p transistors, as long as the collector supply voltage and the direction of current flow are reversed.

A collection of typical characteristic curves for a common emitter transistor are shown in *figure 3*. A line has been drawn between the maximum output voltage (12 V) and the maximum collector current required, say, 2 mA. This is known as a **load line** and from it we can make quite an accurate estimate of the bias current required.

The **operating point**, P, on the load line lies at the intersection of two lines drawn from the voltage which we would like at the output, i.e. 6 V, and the required standing collector current (known as the **quiescent current**) of 1 mA. Point P, in this example, also lies on the base current curve of 4 μA, so this then is the necessary bias current for the circuit to operate according to our requirements.

Consider now what happens when an AC signal is applied to the base. On the signal's positive half-cycle, the signal current, say 4 μA, will combine with the 4 μA bias current, producing a greater overall base current of 8 μA. This 8 μA base current curve on the characteristics in *figure 3* crosses the load line at point B. At this point, the collector current has increased almost to 2 mA and the voltage



3. A collection of typical characteristic curves for a common emitter transistor, showing the operating point, P.

Right: example of the use of extremely high output power amplifiers, shown in the bottom left-hand corner.

Ace Photo Agency/John Strathatos

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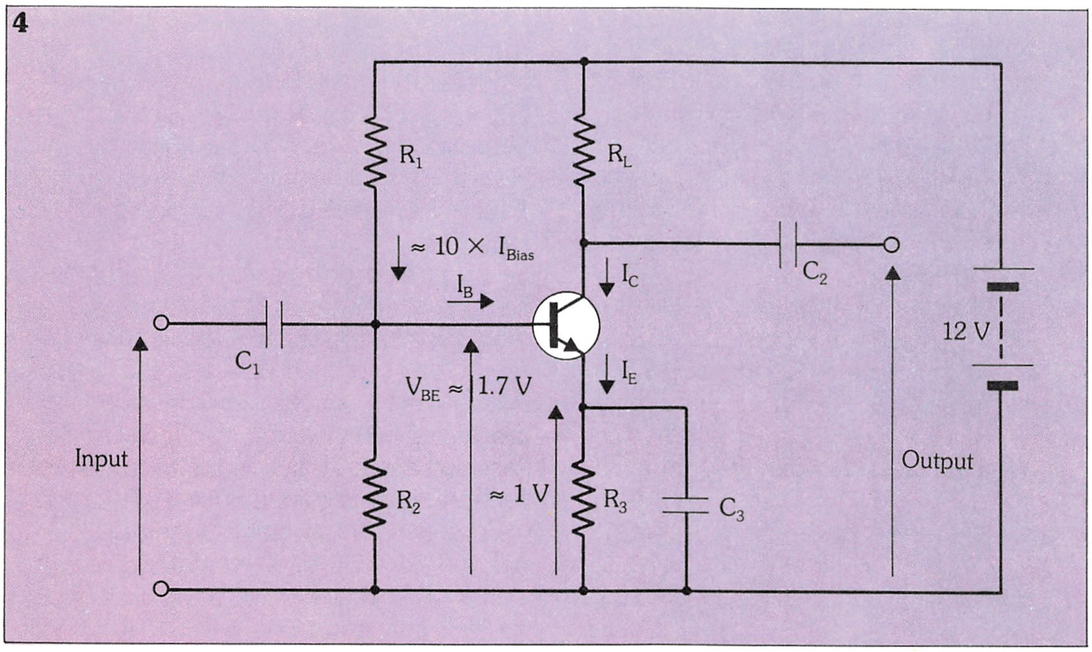


4. The normal method for stabilizing bias current.

across the transistor is almost 0 V. Increasing the base current further does not give a corresponding increase in collector current because the transistor is fully on and cannot be turned on any further. The transistor is said to be **saturated** – this is the exact opposite of cut-off.

Negative half-cycles of signal current subtract from the bias current, so when $-4\ \mu A$ of signal current combine with $4\ \mu A$ of bias current, $0\ \mu A$ of base current flows into the transistor. This, of course, is cut-off and is indicated as point A on the load line.

From the operating point, P, and the load line, the necessary quiescent operating bias current and the quiescent operating output voltage can be defined. Also, by altering the base current, the operating point can be moved along the load line to any required position.

It only remains for us to calculate the values of the load resistor R_L, and the bias resistor R_B.

Resistor R_L is calculated from Ohm's law as we know the voltage across it and the quiescent current through it, so:

$$R_L = \frac{V}{I} = \frac{6}{1 \times 10^{-3}}$$
$$= 6000\ \Omega$$

Similarly, resistor R_B is:

$$R_B = \frac{(12-0.7)}{4 \times 10^{-6}} = \frac{11.3}{4 \times 10^{-6}}$$
$$= 113{,}000\ \Omega$$

Fixed biasing configurations in transistor circuits aren't often used because the gain of the circuit, that is:

$$\frac{\text{output current}}{\text{input current}} = \frac{I_C}{I_B}$$

is totally dependent on the transistor's current gain, $\boldsymbol{\beta}$. As the value of $\boldsymbol{\beta}$ changes from transistor to transistor, and also varies greatly with temperature, it is impossible to accurately define a stable operating point (remember, the characteristics are shown for a single temperature of 25 °C) and circuit gain for this circuit. However, other biasing circuits exist.

Self-bias

The usual method to stabilize bias current is shown in the circuit in *figure 4*. The emitter resistor, R_3, is chosen to be a value such that the DC voltage across it is about 3 to 4 V. So, with a quiescent current of 1 mA, its value is approximately:

$$R_3 = \frac{3}{1 \times 10^{-3}}$$
$$= 3000\ \Omega$$

The potential divider chain of R_1 and R_2 is calculated so that the voltage at the transis-

Table 1
Summary of parameter values for different circuits

Parameter	Common emitter	Common collector	Common base
Current gain	high (50 to 300)	high (50 to 300)	low (≃0.99)
Voltage gain	high (50 to 250)	low (≃0.95)	high (50 to 250)
Input resistance	medium (600 Ω to 2 kΩ)	high (up to 100 kΩ)	low (≃20 Ω)
Output resistance	high (≃50 kΩ)	low (≃100 Ω)	high (≃1 MΩ)

tor base, V_B, is about 3 V plus the base-emitter threshold voltage of 0.7 V, say, 3.7 V. The resistor values are chosen so that the total current flow through the chain is at least ten times the required bias current of 4 μA. So R_1 is about 200 kΩ and R_2 is about 90 kΩ – a high degree of accuracy isn't necessary.

If a temperature increase occurs, the collector current, I_C, and hence the emitter current, I_E, both increase. Any increase in emitter current causes an increase in the voltage across the resistor R_3. The base voltage is fixed at 3.7 V so the base-emitter voltage V_{BE} must fall below 0.7 V, automatically reducing the emitter current and therefore reducing the voltage across the resistor R_3. Bias current is stabilized and a fixed operating point is obtained, almost regardless of temperature variations.

Capacitor C_3 is included in the circuit to prevent the applied AC input signal producing the same effect, as it varies the base current, and thus reducing the effective small-signal gain. Because a capacitor is a virtual short circuit to AC signals, the AC variations produce no change in emitter current. A capacitor is, however, open circuit to the bias DC voltages and so the bias current is not affected.

Values for the various parameters of this circuit, such as gain, input and output resistance, vary with the values of components used. From the typical values summarised in *table 1*, you can see that the circuit generally has a high voltage gain with a medium input resistance, making it a useful circuit for a number of applications.

Table 2
Applications of common emitter, common collector and common base transistor circuits

Common emitter	Common collector	Common base
Used as general purpose, low-power amplifier stages in amplifiers of many different types – high-fidelity sound equipment, TVs, radios etc. Its medium resistance input and medium-to-high resistance output, coupled with high voltage and current gains allows its use in the majority of amplifier applications.	Often used in the input stage of pre-amplifiers which are to amplify signals from high resistance output signal sources e.g. transducers and some types of record player cartridges. The high resistance output of the common collector circuit does not load the source's output. High current gain, but low voltage gain allows its use as a buffer, interfacing between high and low resistance parts of a circuit.	The extremely low resistance input of the common base circuit is useful when amplifying signals from sources with low resistance outputs. Typical examples of such a signal source are some microphones and record player cartridges.

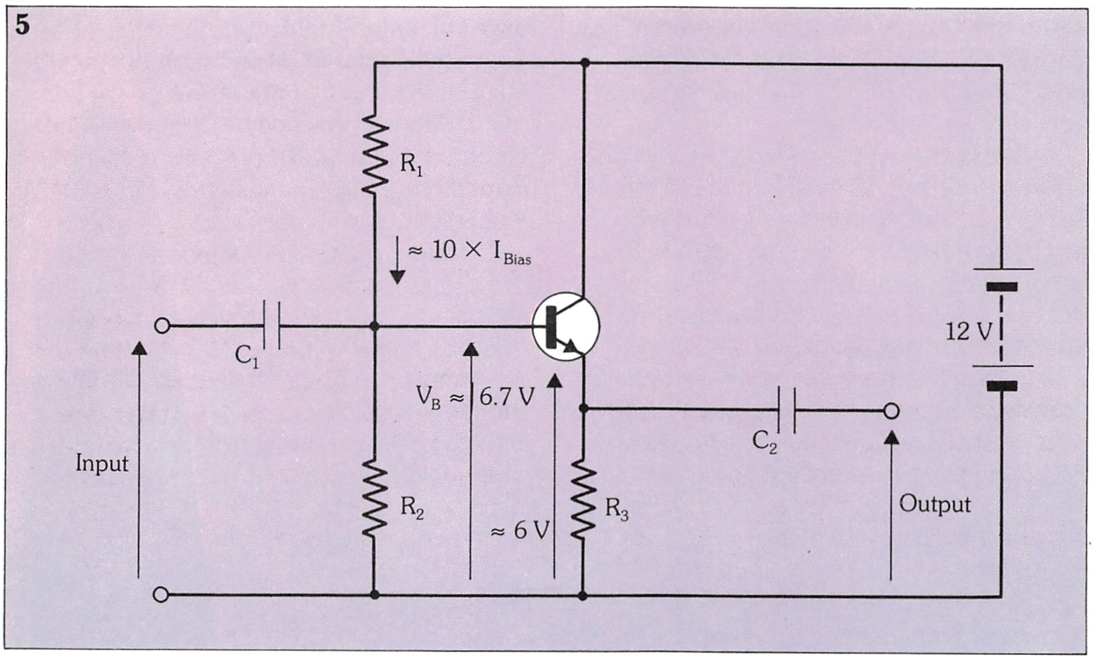
Common collector and base amplifiers

Figure 5 shows a simple common collector transistor amplifier, complete with a similar biasing arrangement to that of the common emitter amplifier. In fact, the bias current is calculated in exactly the same way, but the emitter resistor, R_3, is now also the load resistor and the DC voltage across it should be mid-way between power supply voltage connections, i.e. 6 V.

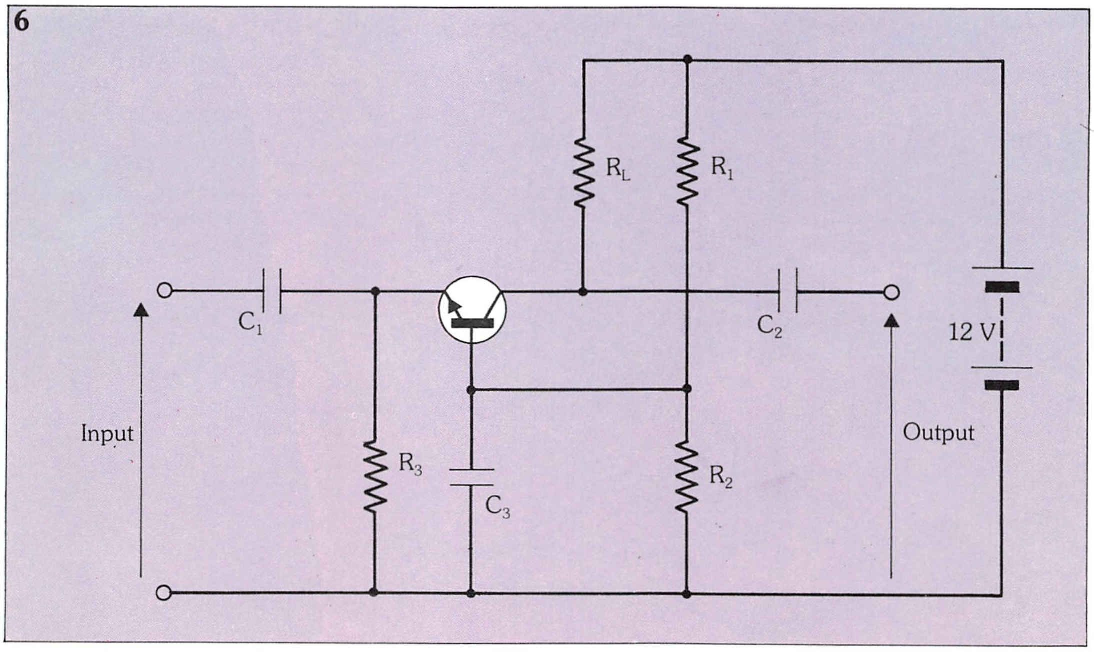
So, the base voltage, V_B, should be about 6.7 V.

How the circuit works

If, say, the applied AC signal voltage increases, then the base-emitter voltage also increases causing a larger emitter current through resistor R_3 – this tends to reduce the base-emitter voltage to its original value. A positive increase of input signal voltage causes a positive increase in output voltage, so the circuit creates no **phase reversal** of signal (unlike the com-



5. A simple common collector transistor amplifier with a similar biasing arrangement to that of the common emitter amplifier.



6. A common base transistor amplifier where bias current is provided by resistor chain R_1 and R_2.

mon emitter). The circiut has no actual voltage gain – in fact it has a slight loss – so we say that voltage gain is about 0.98 to 0.99. The current gain of the circuit is approximately equal to the transistor's current gain, β.

Output voltage closely **follows** the input voltage and the circuit is therefore often called an **emitter follower**.

The usefulness of the common collector lies in the very high input resistance (up to 1 MΩ) and the low output impedance (about 100 Ω or less) of the circuit. This means that it can be used to **buffer** (i.e. follow a circuit which only provides a tiny output current) and provide a larger current.

Common base amplifiers

The circuit in *figure 6* shows a common base transistor amplifier in which bias current is provided by resistor potential divider chain R_1 and R_2. However, bias stabilization is not required for a transistor in common base mode.

Load lines can be drawn on the transistor's common base characteristic curves and a large-signal operating point can be chosen in exactly the same way as that of common emitter and common collector modes.

The circuit works as follows. A quiescent emitter current flows out of the emitter through resistor R_3 to ground. If the applied input signal goes positive, it will tend to lower the emitter current and hence lower the collector current. This causes a decrease in voltage across resistor R_L and thus an increase in output voltage. Obviously, the output voltage is of the same phase as the input voltage.

Capacitor C_3 is used as it was in the common emitter circuit of *figure 4*, to prevent AC small-signals affecting the circuit's AC gain by *shorting* them to ground.

Input resistance of a common-base circuit is very low and current gain is just less than 1. These factors limit use of the circuit to applications such as microphone amplifiers (certain microphones have very low output resistances). Voltage gain, however, can be quite high.

To summarise, using transistors in simple amplifiers is largely a matter of following two logical steps. First, a proper operating point should be established using characteristic curves and a load line. Second, the operating point should be maintained by biasing the transistor correctly, to take into account both variations in operating temperature and devices.

Glossary

bias current	base current or collector current required by a transistor to ensure it functions in its operating range
base current	simple method of attempting to stabilize a transistor's operating point
large-signals	DC standing voltages and currents within a transistor amplifier
load line	line drawn on the characteristic curves of a transistor to define the bias current required for a particular operating point
operating point	point chosen on a load line where the base bias current intersects the load line
quiescent current	standing current in transistor amplifier with no applied AC input signal
small-signals	various AC signals superimposed on the large-signals of a transistor amplifier
transistor cut-off	point in a transistor's operating range when the transistor is fully off

Mechanical effects of a current

We have found that a current carrying wire in a magnetic field distorts the flux pattern (*figure 1*). Because the flux density is much higher on one side of the wire than the other, and lines of flux tend to contract in length and expand in width, the wire will tend to be pushed to the left in this case. The force that pushes the wire is caused by the interaction of the current with the magnetic flux. The magnitude of this force, F (measured in newtons), is given by:

$$F = B \times I \times l$$

where B is the flux density in teslas, I is the current in the wire in amperes and l is the length of the conductor in metres.

The direction of the mechanical force can be found by either sketching the lines of flux (as in *figure 1*), or by applying Fleming's left hand rule: hold your left hand as shown in *figure 2*, with the thumb, first finger and second finger at right angles to each other. If you point your **F**irst finger along the direction of the **F**lux, and the se**C**ond finger along the direction of the **C**urrent, then the thu**M**b will point in the direction that the wire carrying the current will tend to **M**ove, indicating the direction of the force acting on the wire. It is very important to remember that the force is at right angles to both the flux and the current.

Looking at the formula above, we can give a definition for the tesla – the unit of flux density. A current of one amp flowing in a wire one metre long, situated in a magnetic field having a flux density of 1 tesla, will experience a force of 1 newton.

The effect of flux on a coil carrying current

A very common application of this electromagnetically generated force is in electric motors. Whether the motor is designed to run off direct or alternating voltage, the conductor usually takes the form of a coil of wire which is suspended between the poles of an electromagnet.

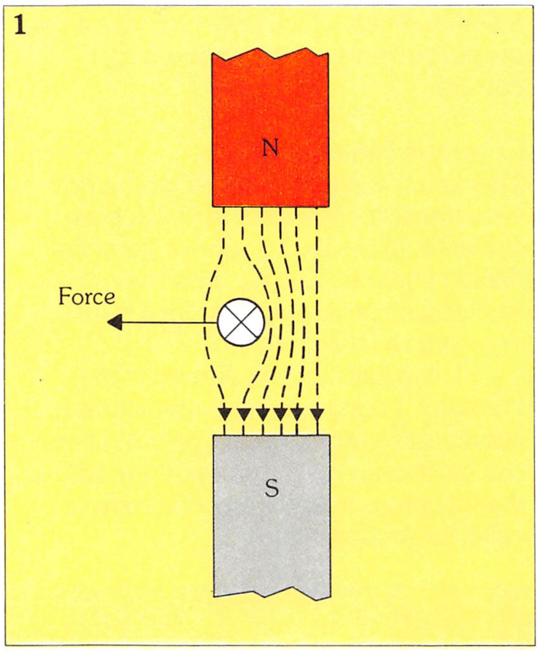
Figure 3 shows an example of an electric motor which, for the sake of simplicity, only uses a single turn of wire; a cross-section of this motor is shown in *figure 4a*, where the coil lies along the centre line of the flux. The current flows down the bottom end of the coil, and up the top end. The density of the magnetic flux passing from the north to south pole is B webers.

The force, F, acting on the upper part of the coil is found (by Fleming's left hand rule) to act to the right. The magnitude of the force is given by:

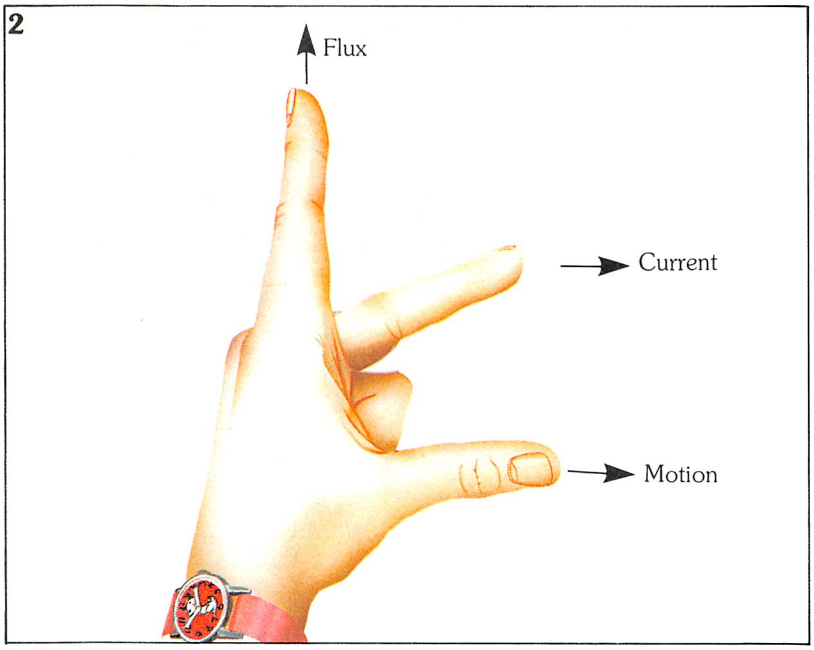
$$F = B \times I \times l$$

where l is the length of the coil lying in the magnetic field. An identical force acts towards the left on the lower half of the coil. These two forces combined will tend to rotate the coil around its central axis, 0.

The most convenient measure of the effect of these forces in rotating the coil about its centre is **torque** (sometimes called a **mo-**



1. A current carrying wire in a magnetic field distorts the flux pattern.

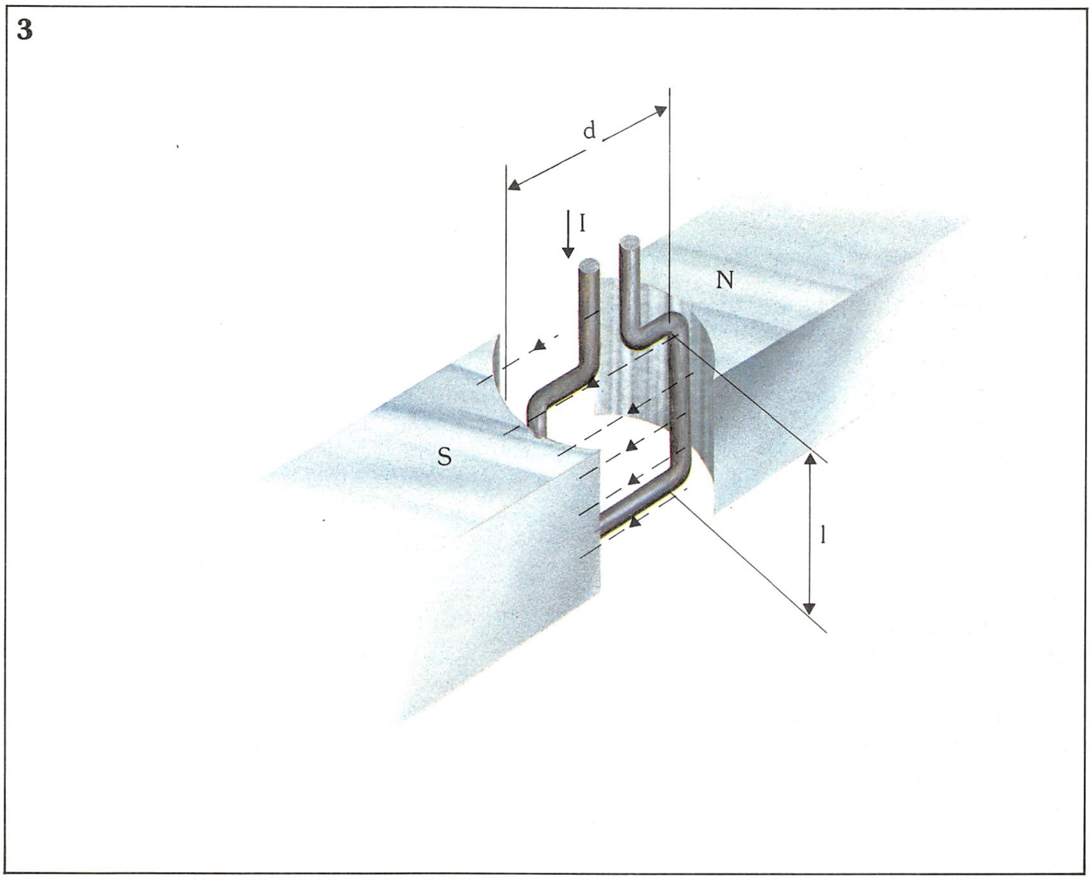


2. Fleming's left-hand rule.

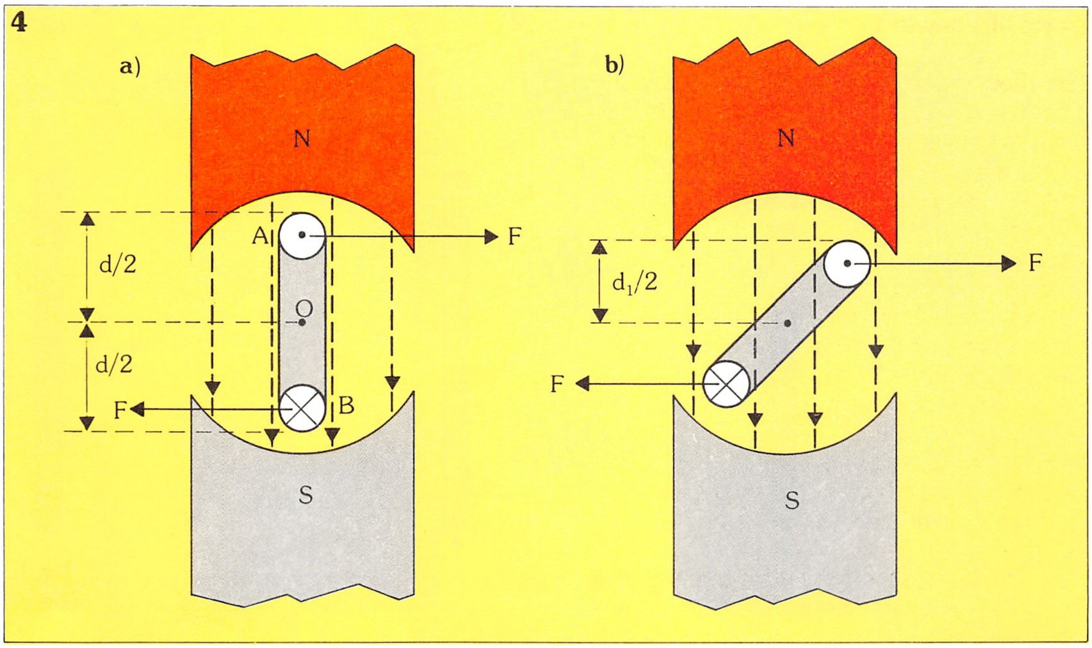
ment). Torque is defined as the product of the force and the perpendicular distance between the force and the rotational axis. In the case of our example, this distance is d/2, and the torque produced on the upper side of the coil is given by:

$$T_1 = F \times \frac{d}{2}$$

and it acts clockwise around the axis. Similarly, the lower side of the coil will give a clockwise torque, T_2, of the same magnitude. The total torque, T, on this single turn of wire is the sum of T_1 and T_2:



3. An example of a simple electric motor using only a single turn of wire.



4. A cross-section of the motor shown in figure 3 where (a) the coil lies along the centre line of the flux; and **(b)** the coil is not parallel to the lines of flux.

$$T = T_1 + T_2$$
$$= F \times d$$
$$= B \times I \times l \times d$$

If the coil is not parallel to the lines of flux, *figure 4b*, then the forces on the two sides of the coil will be the same, but the perpendicular distance to the axis $d_1/2$ is now less than d/2, so the torque in this position will be smaller than before.

The force between two current carrying wires

Figure 5a illustrates another situation in which a mechanical force is set up in a current carrying system. Two parallel wires, a considerable distance apart, carry currents I_1 and I_2, which flow in different directions. The flux patterns for these wires are shown. Although they are drawn as overlapping, they are in fact far enough apart to have little effect on each other.

However, if we move the two wires closer together (*figure 5b*) the lines of flux passing between the wires will be compressed closely together. As we know, this means that they are trying to force the two wires apart, and we can now try to find the magnitude of this force.

If the wires are l metres long and separated from each other by a distance of d metres, then the field strength in the right-hand wire that is caused by the current in the left-hand wire is given by:

$$H_2 = \frac{I_1}{2\pi d}$$

The flux density at this wire (assuming that the wires are in air) is given by:

$$B_2 = \mu_0 \times H_2$$

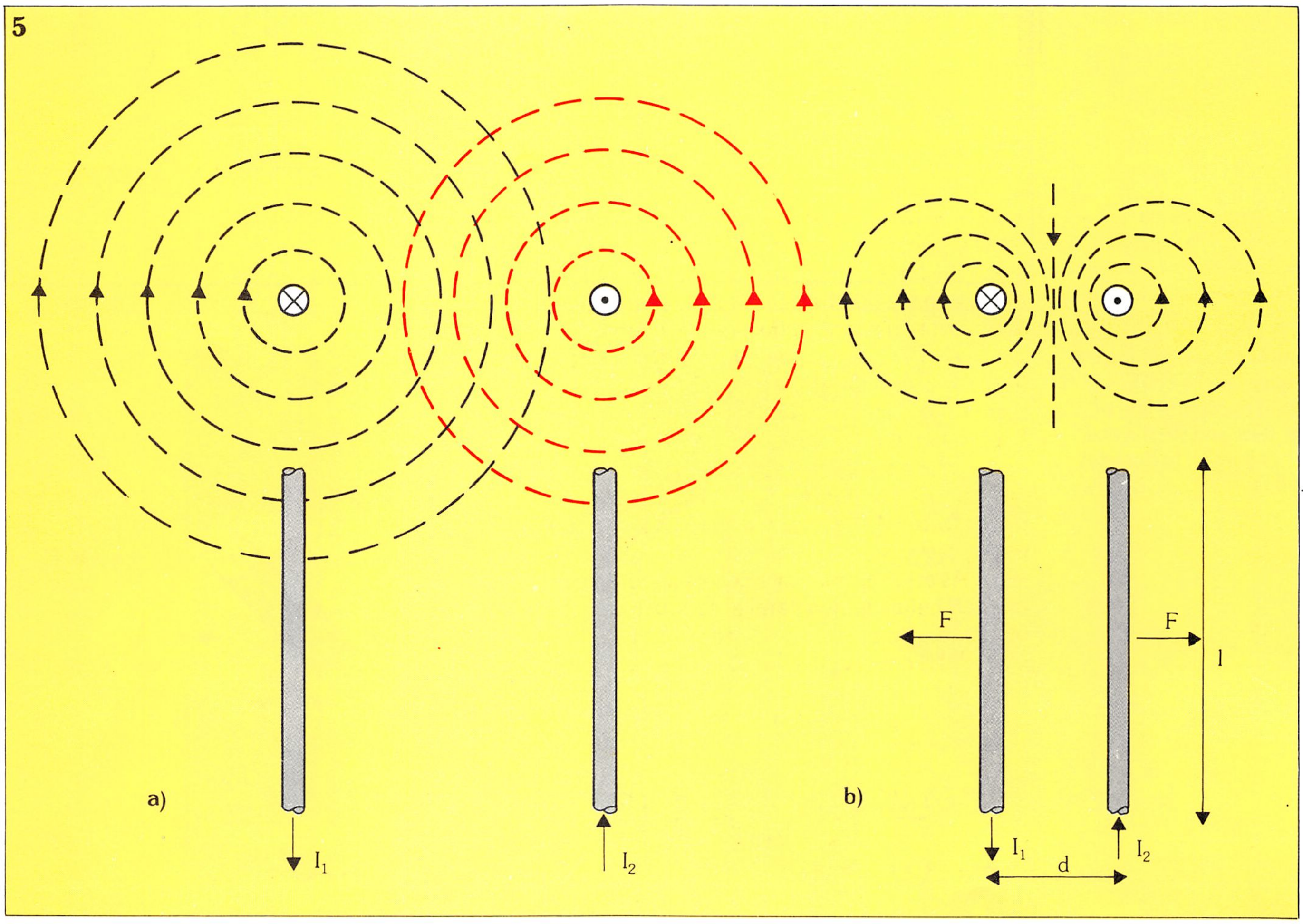
hence the mechanical force is:

$$F = B_2 \times I_2 \times l$$
$$= \frac{\mu_o \times I_1 \times I_2 \times l}{2\pi d}$$

We would have obtained the same expression if we had started off with the current in the left-hand wire, causing a flux at the right-hand wire. Fleming's left hand rule shows us that the force is directed so as to push the wires apart.

If we were to take the same two wires, replace them at their original distance apart, and send currents down them in the same

5. Two parallel wires carrying currents which flow in opposite directions: (a) the wires are a sufficient distance apart so that the flux lines from each wire have little effect on each other; **(b)** the two wires move closer together, compressing the lines of flux.



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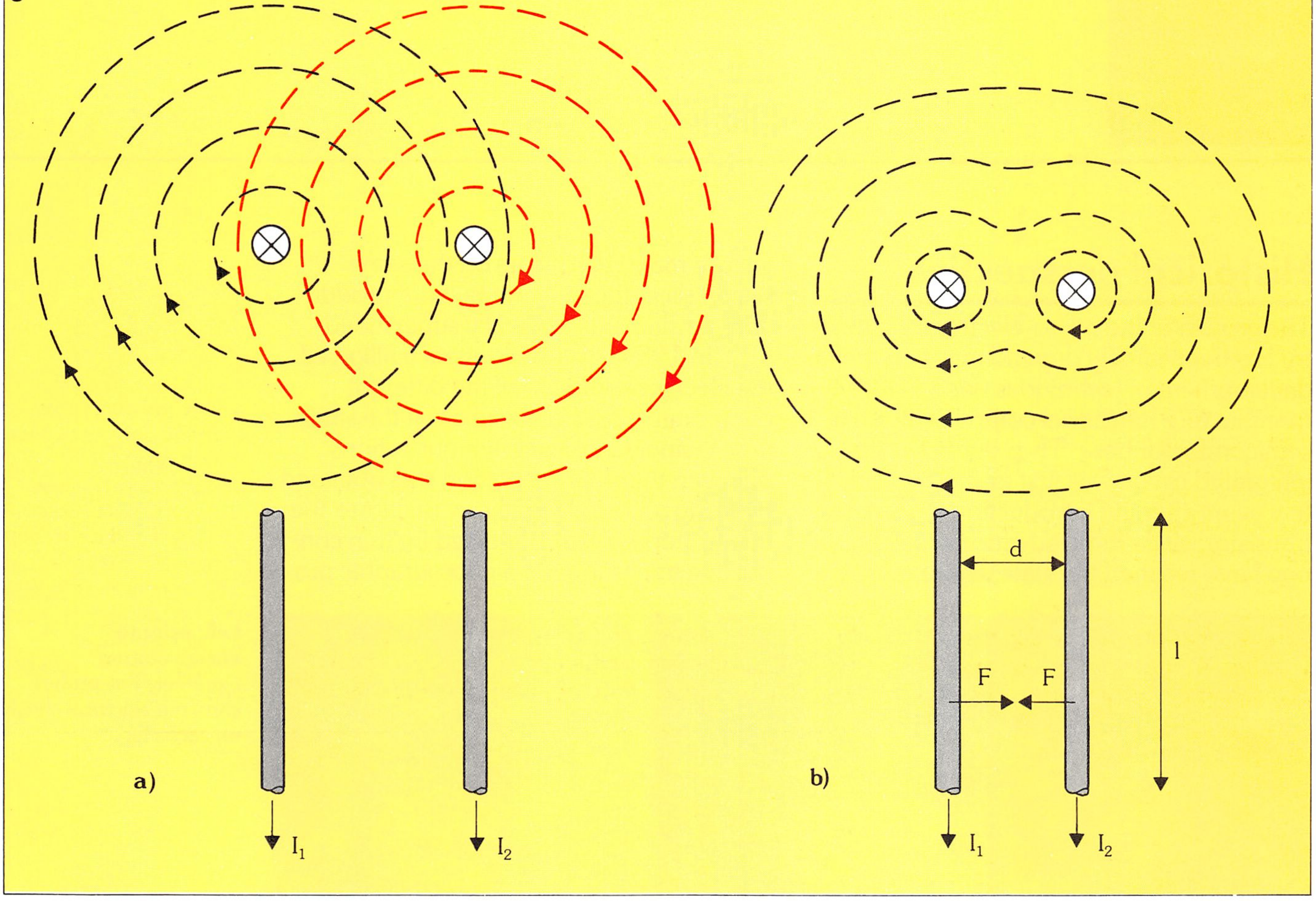


6. The same two wires as shown in figure 5 with currents flowing in the same direction: (a) the wires are sufficient distance apart so as the lines of flux have little effect on each other; **(b)** the two wires move closer together, amalgamating the lines of flux.

direction, then the lines of flux around the two wires would be as shown in *figure 6a*. Here again the lines of flux are drawn as overlapping to save space and because they are far enough apart not to have any effect on each other. If we move the wires closer together (*figure 6b*) then we can see that the lines of flux amalgamate to give the flux pattern shown. Because lines of flux tend to contract, we can see that there will be a force on each conductor, attracting it towards the other. The magnitude of this force will be found in the same way as used previously.

As an example, let's determine the force exerted between two parallel conductors, 60 cm long, each carrying a current of 15 A, placed 0.8 cm apart in the air. The force is given by:

$$F = \frac{\mu_o \times I_1 \times I_2 \times l}{2 \pi d}$$

$$= \frac{1.257 \times 10^{-6} \times 15 \times 15 \times 0.6}{2 \times 0.008}$$

$$= 3.37 \times 10^{-3} \text{ N}$$

□

10

DIGITAL ELECTRONICS

IC manufacture

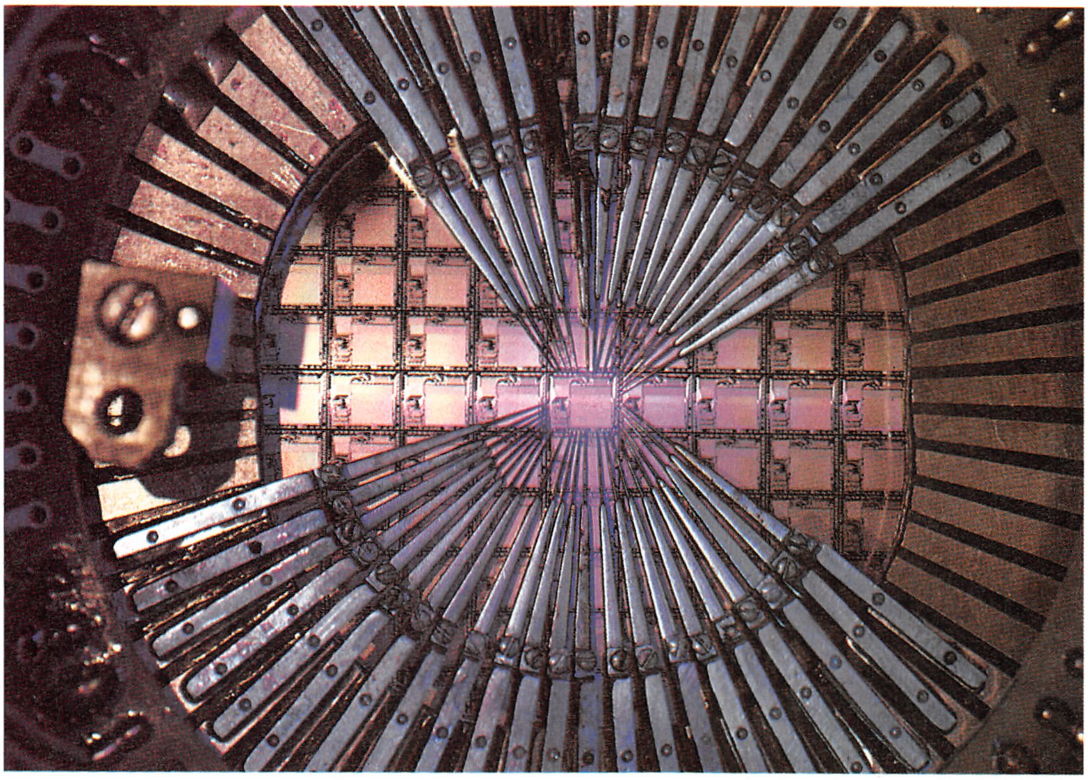
Historical perspective

The growth of the micro-electronics industry has been largely dependent upon the development of techniques needed to manufacture functional components on a semiconductor base. The concept of an integrated circuit was first formed only a few years after the introduction of the transistor; since then, advances in technology have reached the state where more than 100,000 gates can now be manufactured on a single chip.

Thinking back to *Solid State 10*, you will remember that the solid state diffusion method, developed in the mid-fifties, was used to dope semiconductor base material, creating n and p-type zones. Selective diffusion using photographic methods then made it possible to simultaneously manufacture many transistors on the same silicon slice; the old 'one by one' production method was gradually superseded.

In 1959, a further advance alllowed the electrical isolation of the different components on a slice, whilst at the same time laying down the interconnections between them. The isolation was obtained by using reverse-biased p-n junctions; the components were connected by thin conductive tracks. Again, a photographic process was used.

Since then, technological improvements have meant that both reliability and operational speed have been increased, together with the complexity of circuits and the density of integration possible. Now, integrated circuits are mass produced in their hundreds of thousands, costing less than a few pence each.



Left: prior to encapsulation, extremely fine probes carry out electrical checks on each chip.

Growth and diffusion

Silicon, the base material used to make most semiconductor devices, has two essential requirements: a high degree of purity (impurity level tolerances are less than one part in 10^{10}); and a continuous, regular monocrystalline structure. The methods used to purify polycrystalline silicon and convert it to monocrystalline form were covered in *Solid State 10*, so let's take a detailed look at some of the processes used to make an IC's circuit elements.

Epitaxial growth

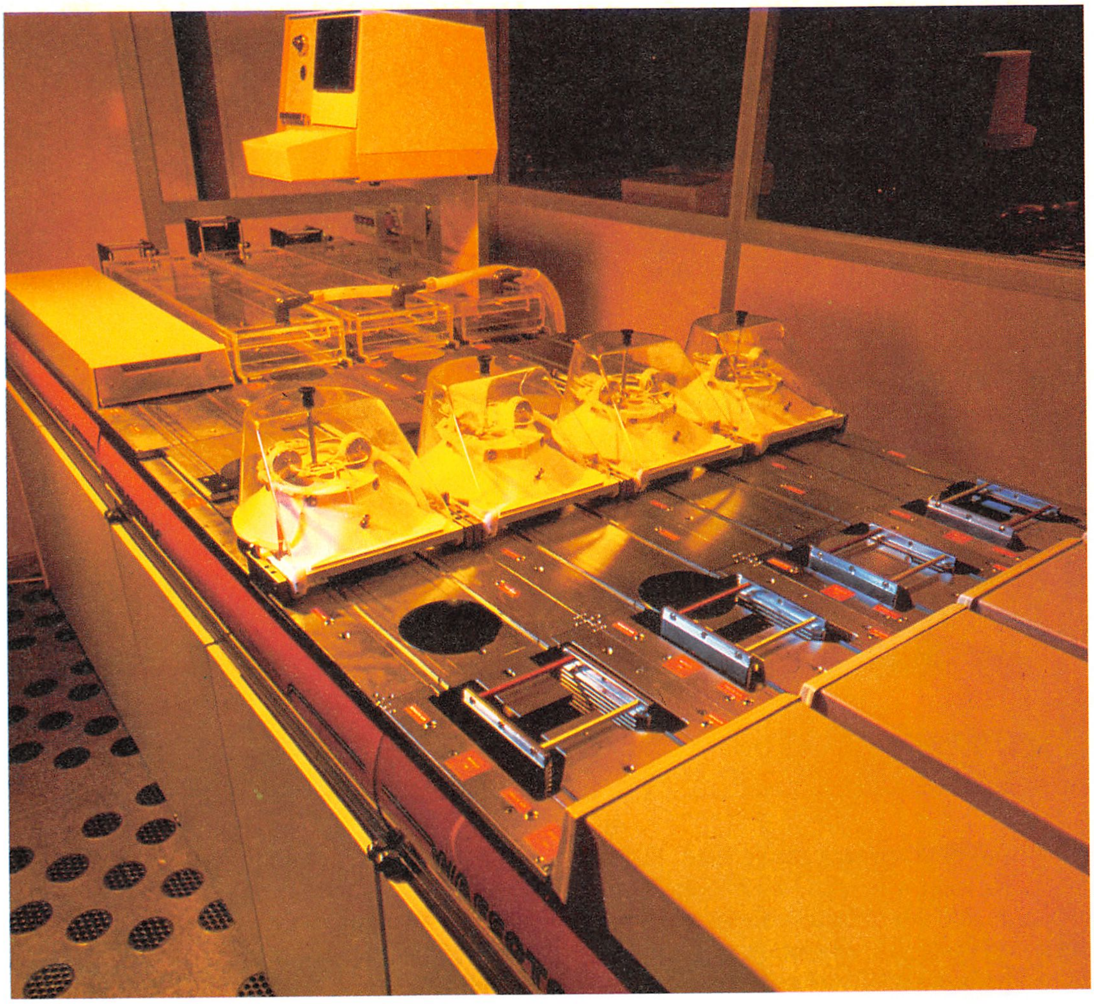
When monocrystalline silicon is manufactured it is doped with either a p or n-type impurity depending on its final use. As we know, semiconductor devices depend on p-n junctions – the epitaxial growth method is used to form a layer of doped monocrystalline silicon some tens of micrometres thick on top of a monocrystalline wafer without any discontinuity in the crystal lattice at the junction.

This method utilises a sealed reaction chamber (made of quartz) heated to 120 °C, into which gas is pumped. The silicon wafers are placed inside, on a graphite 'boat'. A mixture of silicon chloride and hydrogen is used to provide the epitaxial growth, while phosphene or boronethane, respectively, provide the required n and p-type doping. The high temperature of the chamber brings about the liberation of pure silicon atoms and doping agents. The silicon is regularly and uniformly deposited on the surface of the wafer, while atoms of the doping agent are simultaneously trapped in formation in the crystal lattice.

Solid state diffusion

This process involves the diffusion of p or n-type dopants into an existing silicon layer. By diffusing a p-type dopant, say,

Right: this microprocessor controlled wafer track receives uncoated wafers at one end, covers them with adhesive, spin coats them with photoresist to a thickness of 1µm, and finally rebakes them in an infra-red oven. Wafers emerging from the other end are ready for exposure.
(Photo: Mullard Ltd)



into a previously n-type doped wafer, a p-n junction is made. This is the most widely used method in the manufacture of transistors and ICs. The diffusion occurs when a solid monocrystalline silicon wafer is heated to between 800 °C and 1250 °C in the presence of dopant atoms. The dopant atoms diffuse into the silicon at a rate of about 2.5 micrometres per hour only, depending on the temperature. Because the process is so slow, the depth of the doped monocrystalline lattice layer can be accurately controlled: the value chosen varies between one and ten micrometres.

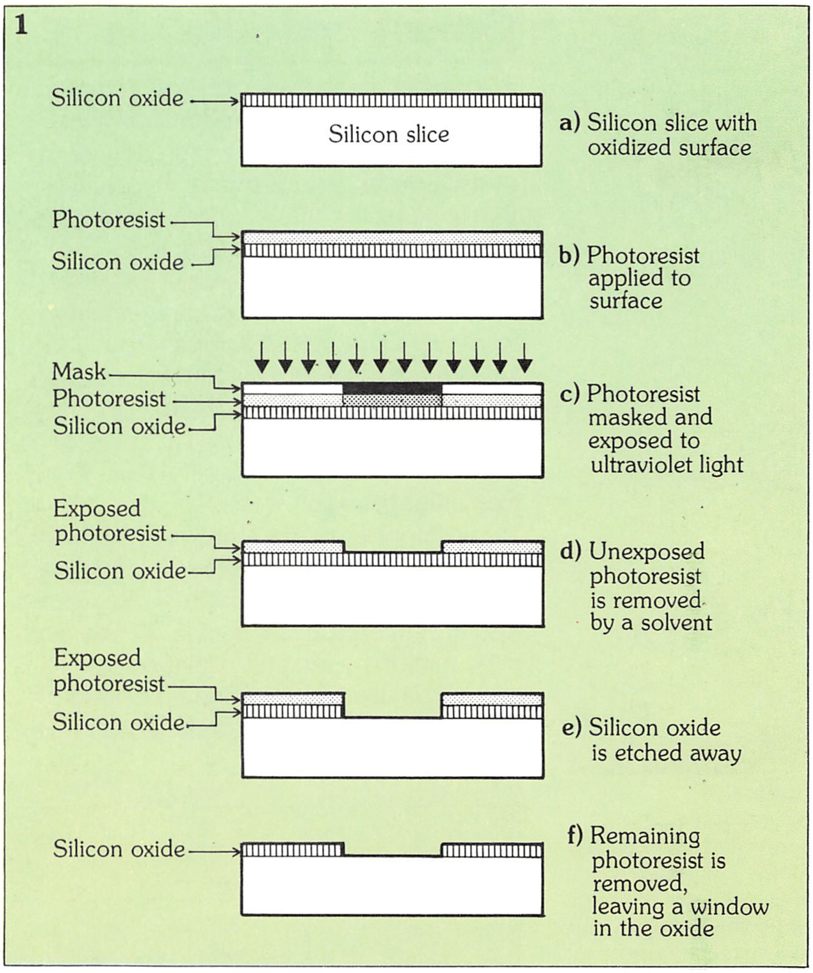
This production method has two stages. Firstly, the heated silicon wafer is exposed to vapours of the dopant causing a high concentration of impurities to be **deposited** on the surface of the wafer. In the second or **diffusion** stage, the wafers are placed in a second furnace operating at a higher temperature. The dopant impurities slowly spread into the crystal and form a layer of decreasing dopant concentration on the surface of the slice.

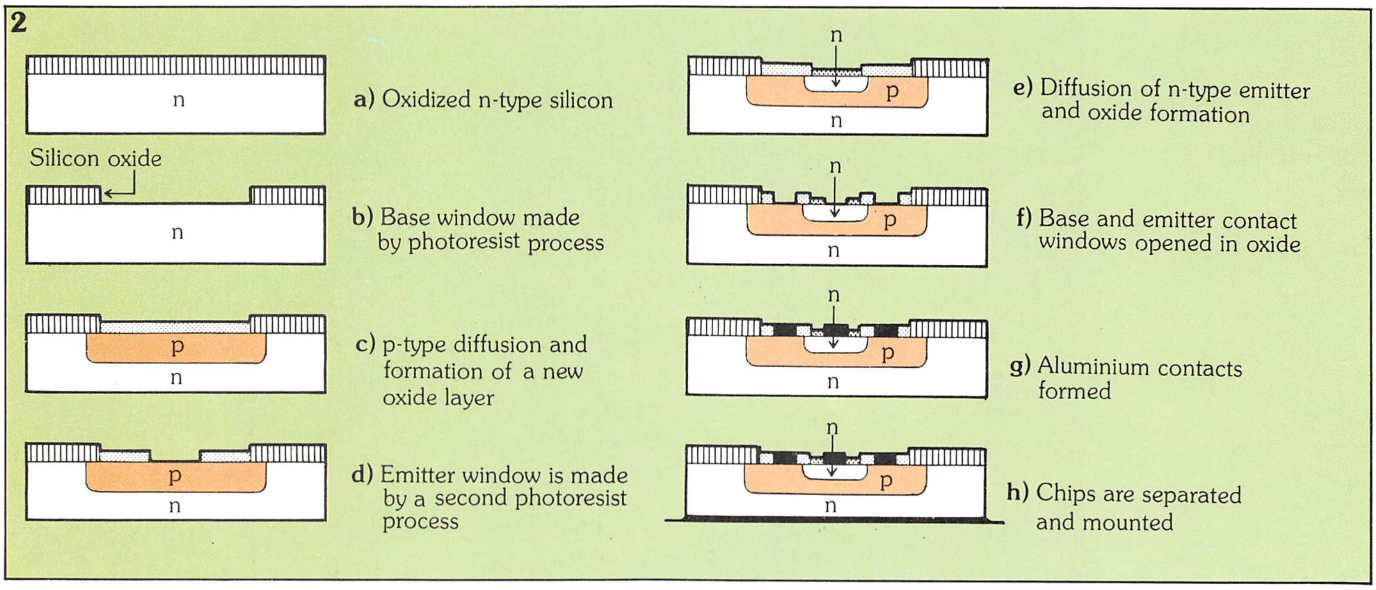
Masking with silicon oxide

In *Solid State 10* we saw how the technique of masking is used to prevent diffusion in certain areas, thereby creating many individual devices on a single slice. Silicon oxide, for example, can be used as it prevents dopant diffusion and is easily removed by a hydrofluoric acid solution.

The wafer is then heated to about 1000 °C in a stream of oxygen, oxidizing the whole surface of the wafer with silicon dioxide.

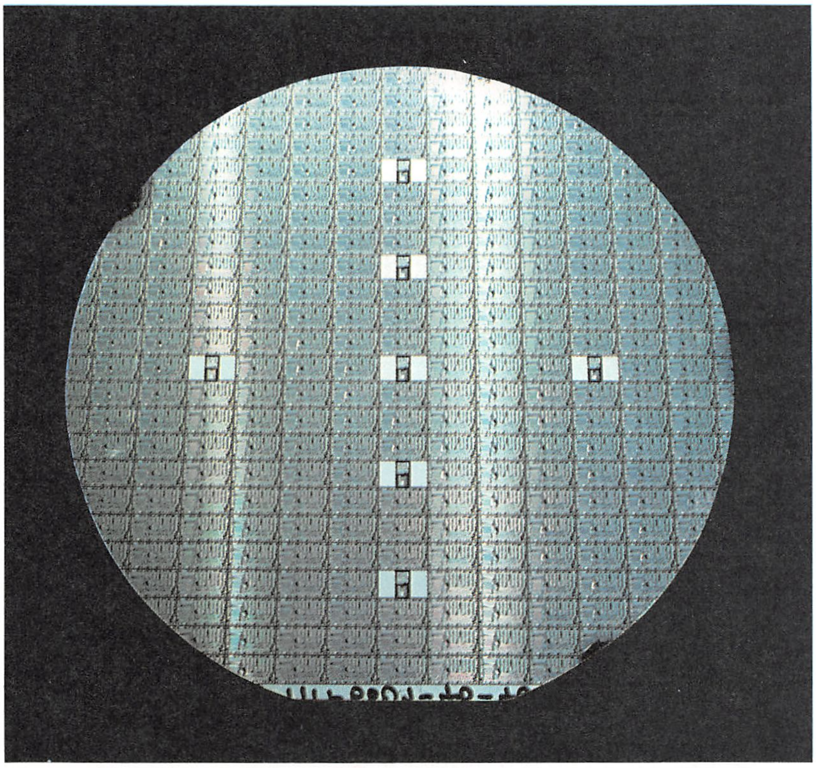
Such selective diffusion methods form the basis of all monolithic integrated





1. Stages in the selective removal of the silicon oxide.

2. Planar diffusion process.



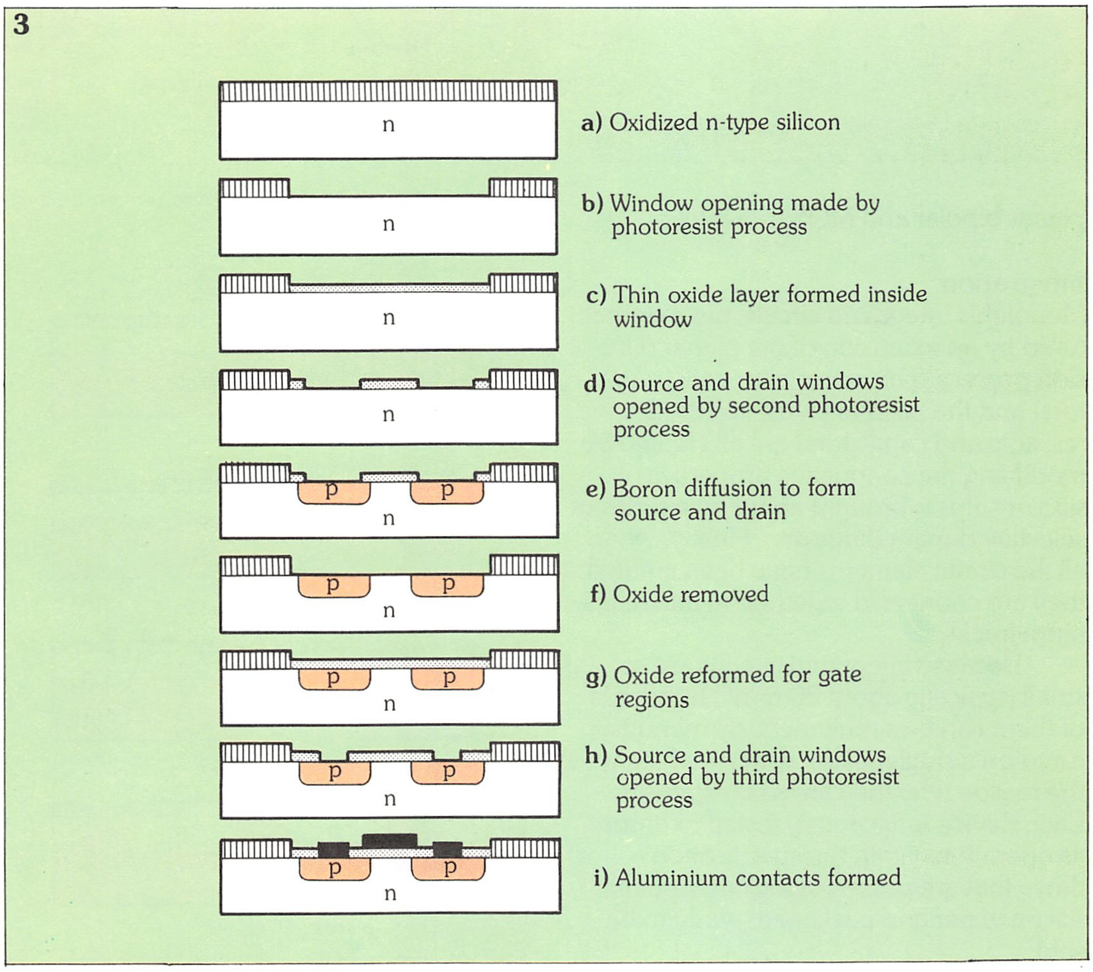
circuit construction, as they allow the formation of a great number of independent components on a single silicon wafer.

The removal of areas for diffusion

The selective removal of the silicon oxide is carried out by another photographic process (*figure 1*). This uses a light sensitive emulsion called a **photoresist**, which is applied to the wafer's oxide layer. A photographic mask is placed above the wafer, which is then exposed to ultraviolet light. Where the mask is transparent, the light will pass through and polymerize the photoresist. The unpolymerized photoresist (i.e. in the dark areas of the mask) is removed with suitable solvents.

The silicon wafer is then immersed in a solution of hydrofluoric acid which removes the unprotected oxide. The photoresist is completely removed and the wafer is now ready to undergo the diffusion process, which will only take place through the little windows that were etched in the

Above: the final silicon wafer contains hundreds of integrated circuits.



3. Planar diffusion process producing MOS transistors.

oxide layer. This process is covered in greater detail in *Solid State 10*.

This technique is of fundamental importance to modern electronics and both discrete and integrated components using planar transistors are made in this way. As we have already met the planar process in *Solid State 10*, *figures 2 and 3* concisely sum-up the manufacture of planar bipolar and MOS transistors.

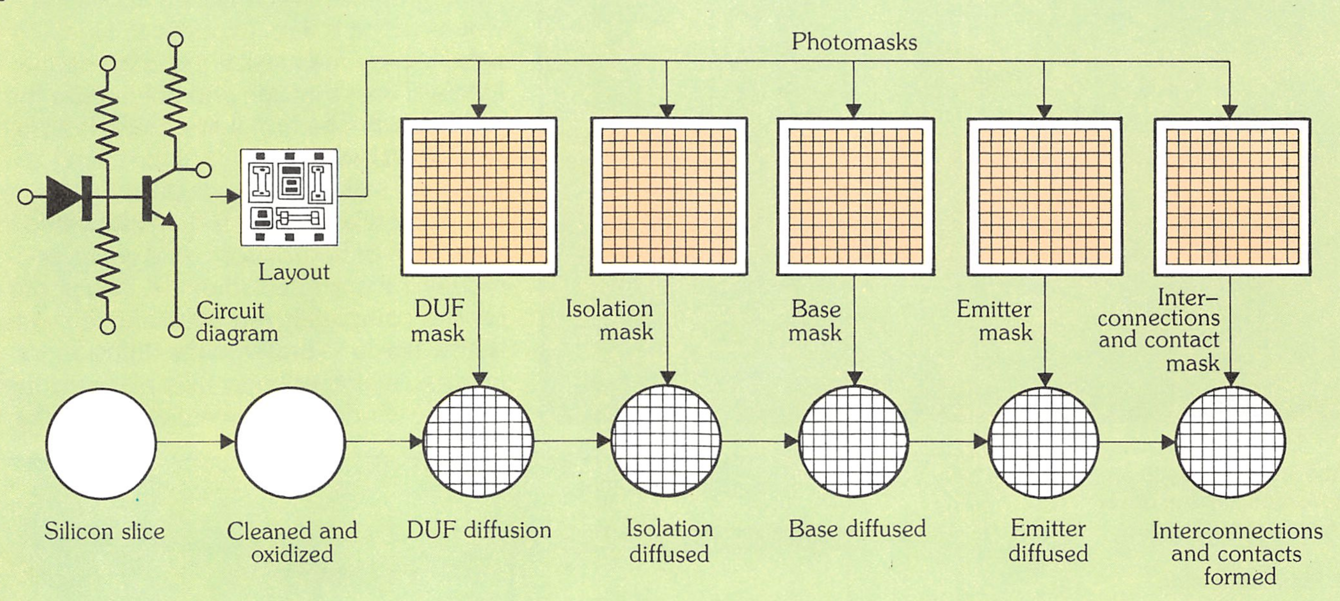
Design

As we have seen, the structure of an integrated circuit is formed by a series of selective diffusions in precise areas of the silicon substrate. The position of these regions is determined by the circuit designer. The basic stages in the design and manufacture of a monolithic integrated circuit are shown in *figure 4*. First, the size

4. The basic stages in the design and manufacture of a monolithic integrated circuit.

5. The p-n junction isolation process.

4



Integration

Monolithic integrated circuits are manufactured by an extension of the planar diffusion process. The active elements (transistors) and the passive elements (diodes, resistors and capacitors) are all created by modifying the conductive properties of silicon – this is brought about by a series of selective dopant diffusions. Finally, when all the circuit elements have been created, they are connected together by thin aluminium tracks.

Because integrated circuits are so small (typically about 20 mm^2) hundreds of them can be simultaneously manufactured on a single silicon wafer – which is the reason why they are so inexpensive. Each device is rigorously tested to ensure its operation within the specification – those that are passed being cut from the silicon wafer and packaged, ready to be sold.

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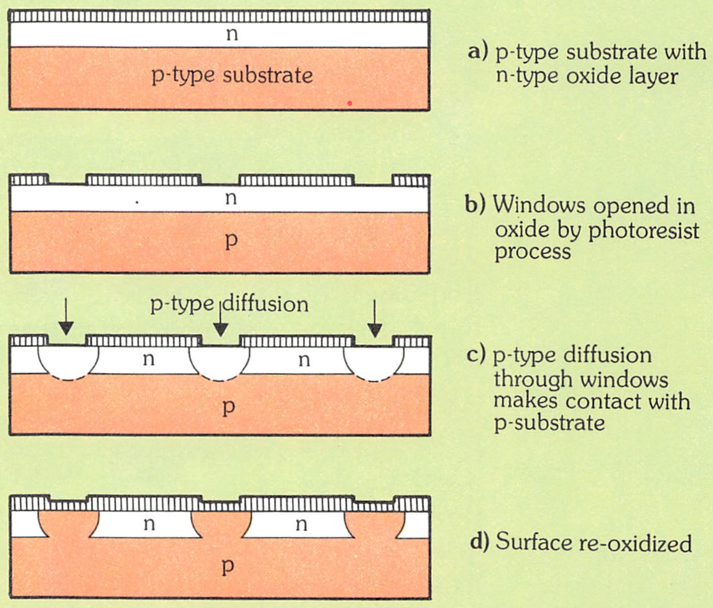

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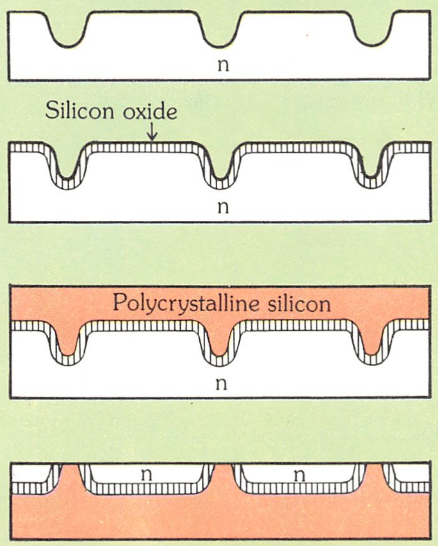

6. The isolation using oxide process.

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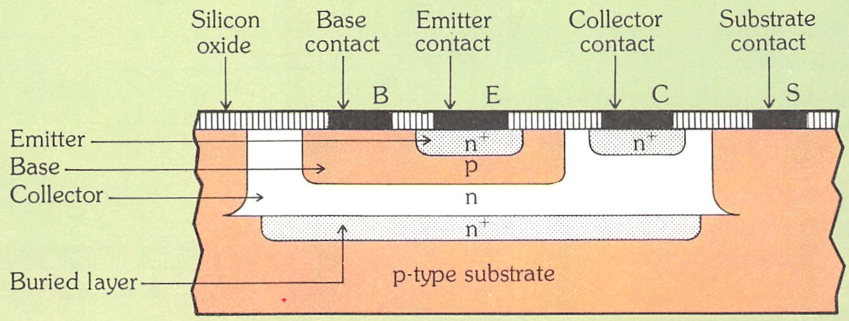

7. The structure of an n-p-n transistor made in a junction isolated region.

and approximate position of each circuit element is estimated; then, a computer is used to work out the most effective, economical and compact arrangement for these elements. The computer produces an enlarged drawing of the chip's layout, from which the designer obtains further drawings of the different diffusion layers and the interconnections. These are then reduced to the actual size of the chip and reproduced hundreds of times on the corresponding working photomask.

Isolation

The first stage in the IC manufacturing process creates electrically isolated zones on the silicon wafer. Each circuit component is made within one of these zones, thereby insulating it from other components. The most common techniques used are **p-n junction isolation** and **isolation using oxide**.

The p-n junction isolation process (*figure* 5) comprises three stages. First, an n-type epitaxial layer is grown onto a p-type silicon wafer substrate. Second, p-type dopant impurities are selectively diffused onto the n-layer, creating many separate p-n junctions. These junctions are then reverse-biased (third stage) by connecting the substrate to the negative circuit supply terminal, thus ensuring that the various regions of the finished element are electrically isolated.

In the oxide isolation method, the various isolated regions are created by using an n-type silicon wafer with a series of channels cut into its surface. As you can see in *figure* 6, the wafer is oxidized and coated with an epitaxial layer of polycrystalline silicon. The individual regions are obtained by grinding down the lower surface of the disk. The thin layer of oxide then surrounding each region ensures their electrical isolation.

Integrated bipolar transistors

Integrated bipolar transistors are made in a similar way to discrete transistors. *Figure* 7 shows the structure of an n-p-n transistor made in a junction isolated region.

The base, p, and emitter, n^+ (indicates a heavily doped n-type material), are obtained by selective diffusion of boron and phosphorus. Along with the emitter, a small n^+ region is formed on the collector, to act as a low resistance electrical contact. The heavily doped n^+ region under the

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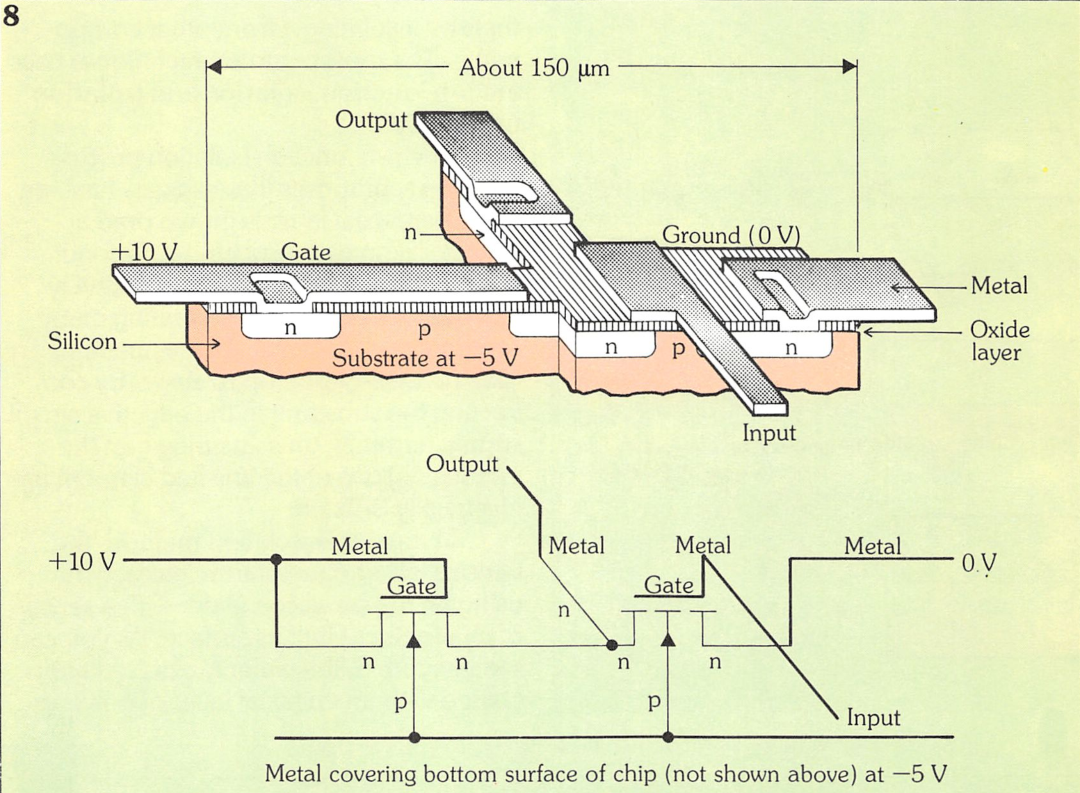
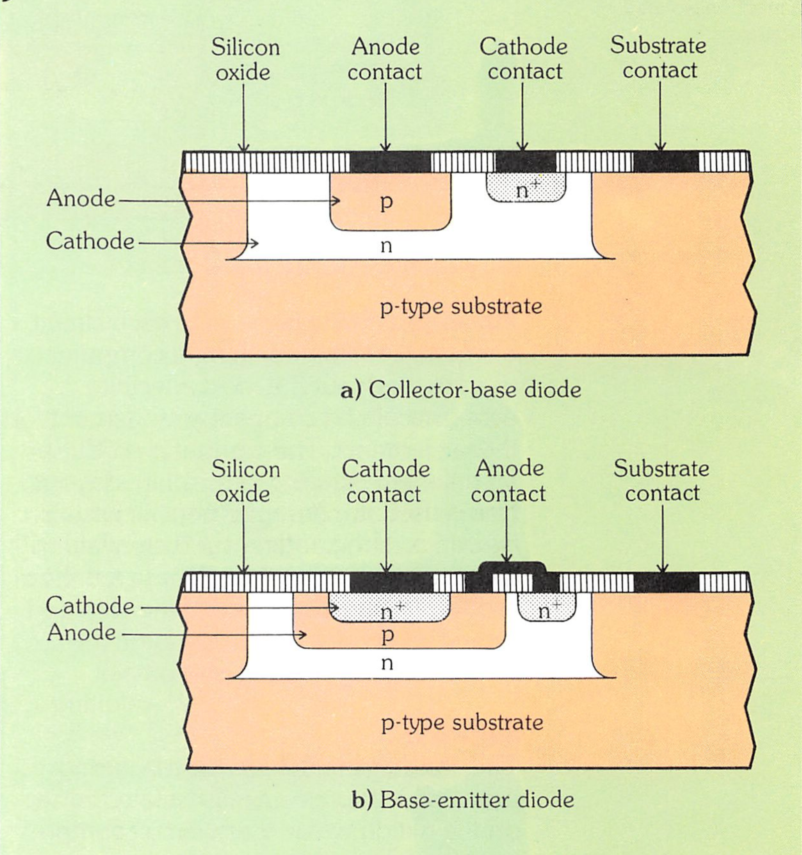


8. How two MOS transistors are fabricated as part of an integrated circuit.

9. The structure of an integrated diode: (a) collector-base; **(b)** base-emitter.

9



transistor is diffused during the isolation process (before the formation of the epitaxial layer). This n^+ layer is made to reduce the electrical resistance of the collector region and so considerably improve the transistor's characteristics.

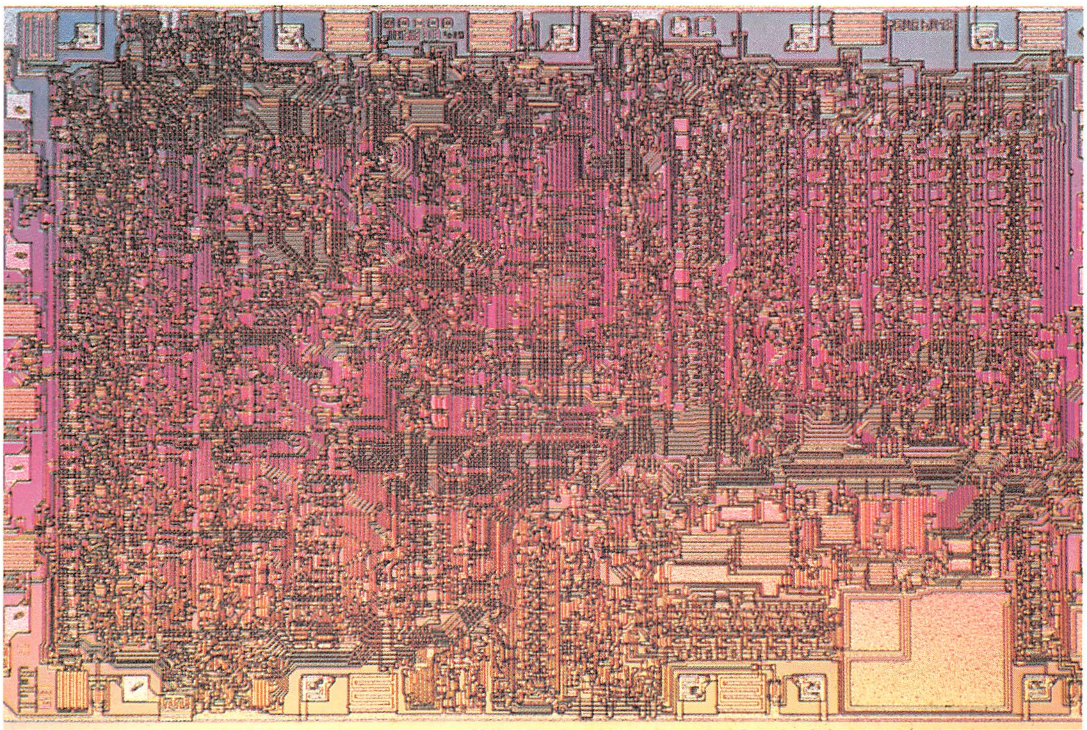
Integrated MOS transistors

As we have seen in *Digital Electronics 2*, the MOS transistor is completely isolated from its substrate. Therefore, when MOS transistors are used as part of an integrated circuit they don't need to be built in an isolated region, being formed in a very small area, thus reducing the manufacturing cost and increasing the integration density. MOS transistors can also be used as resistors: this again improves the integration density of passive components. However, the high resistance of conducting MOS transistors precludes their use in circuits needing a high operating speed. *Figure 8* shows how two MOS transistors (connected to make an inverter) are fabricated as part of an IC.

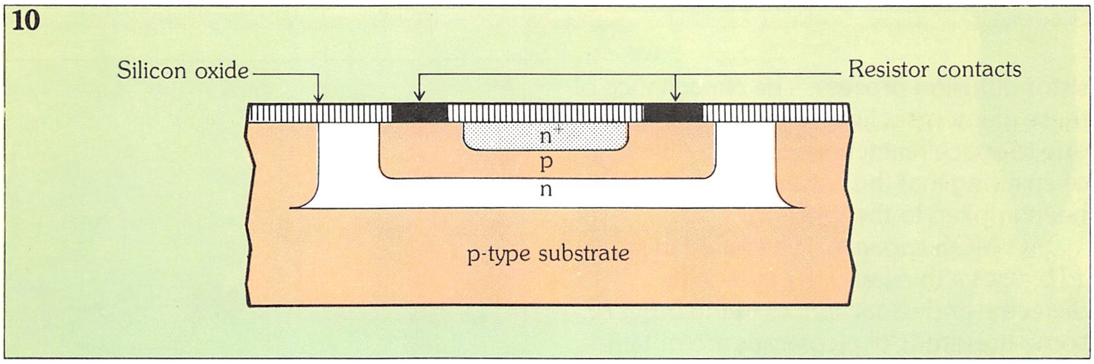
Integrated diodes

Integrated diodes are made by forming a

Right: Lay-out of an IC chip.



10. The structure of a resistor made during base diffusion.



p-n junction at the same time as the transistor diffusion process takes place. The structure of an integrated diode is shown in *figure 9a*. Its anode was made when the transistor bases were diffused. If a high switching speed is needed, the emitter-base junction of a transistor structure is used: this arrangement is shown in *figure 9b*. The anode is short circuited with the n-type region of the diode to avoid any unwanted transistor effects.

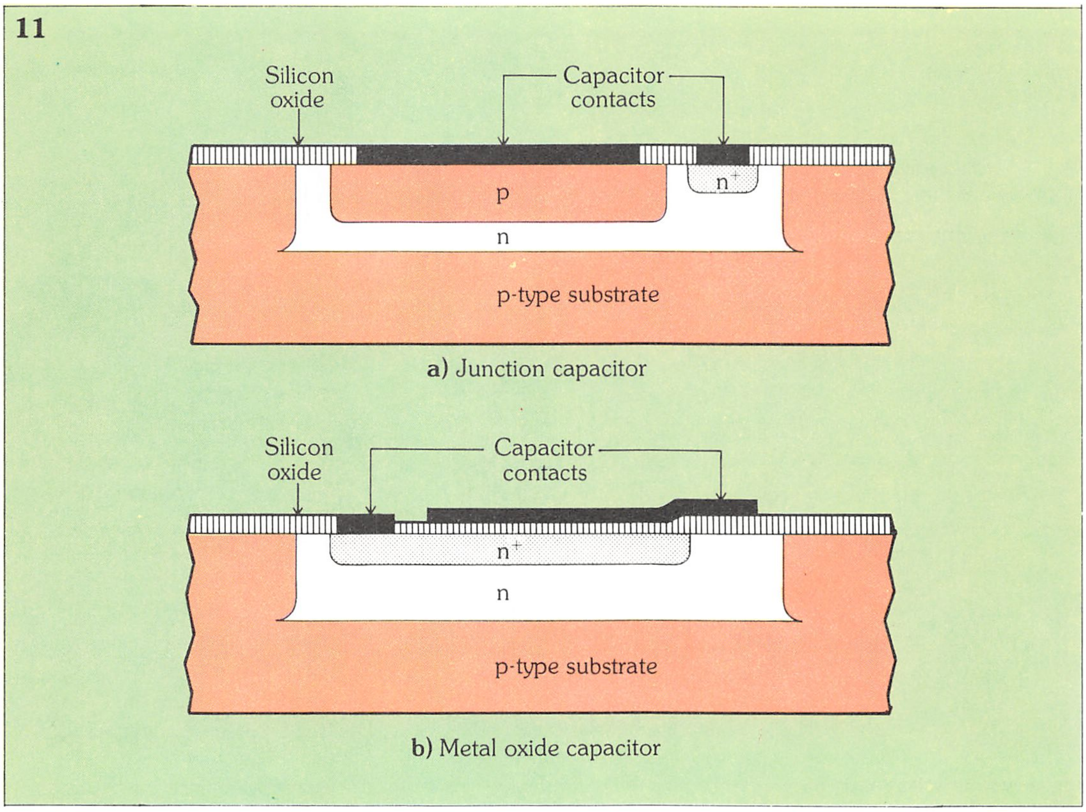
Integrated resistors

Resistors in ICs are made by exploiting the resistance of the isolated region that is diffused during the formation of transistor bases. The resistor takes on a well defined value linked to the requirements of the transistor – this is dependent on the concentration and type of impurity used. These values can range from 20 Ω to 20 kΩ.

The value of the resistor is defined by the length and width of the isolated region. Resistors can be made, quite accurately, with widths down to about 25 micrometres. The maximum possible resistor length is limited by the space available on the chip. *Figure 10* illustrates the structure of a resistor made during the base diffusion.

Integrated capacitors

ICs use two types of capacitor – the junction capacitor and the MOS capacitor. Junction capacitors (*figure 11a*) make use of the capacitance of reverse-biased p-n junctions, and are formed during the tran-



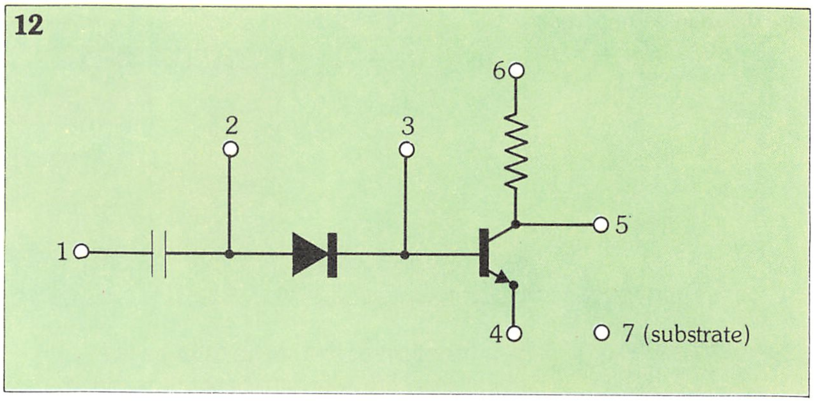
11. ICs use two types of capacitors: (a) junction; **(b)** metal oxide.

12. The actual dimensions of this circuit would be 0.9 mm long and 0.15 mm wide.

13. Side and plan views showing the various stages in the manufacture of the small circuit shown in figure 12.

sistor diffusion process. The capacitance of these elements is limited to about 100 pF, due to space restrictions and the difficulty of ensuring that the correct bias voltage has been applied to the junction.

A MOS capacitor, illustrated in *figure 11b*, uses a thin layer of oxide as its dielectric and capacitances in the order of some hundreds of picofarads are obtainable. The formation of the dielectric involves an additional manufacturing stage. The plates, or electrodes, in a MOS capacitor comprise an n^+ region (obtained during the emitter diffusion process) and a layer of aluminium which is evaporated onto the dielectrics when the connecting tracks are formed.



Building a complete integrated circuit

As you will have gathered, the circuit elements in complete ICs are all formed simultaneously in the sequence: oxidation, selective oxide removed, diffusion and metallization. *Figure 13* shows the stages involved in making the small circuit shown in *figure 12*. As this is an example the circuit is shown to be made in a straight line, but in reality the different elements would be arranged in the most convenient and economical way. The whole process is shown in *figure 13*. The actual dimensions of this circuit would be 0.9 mm long and 0.15 mm wide.

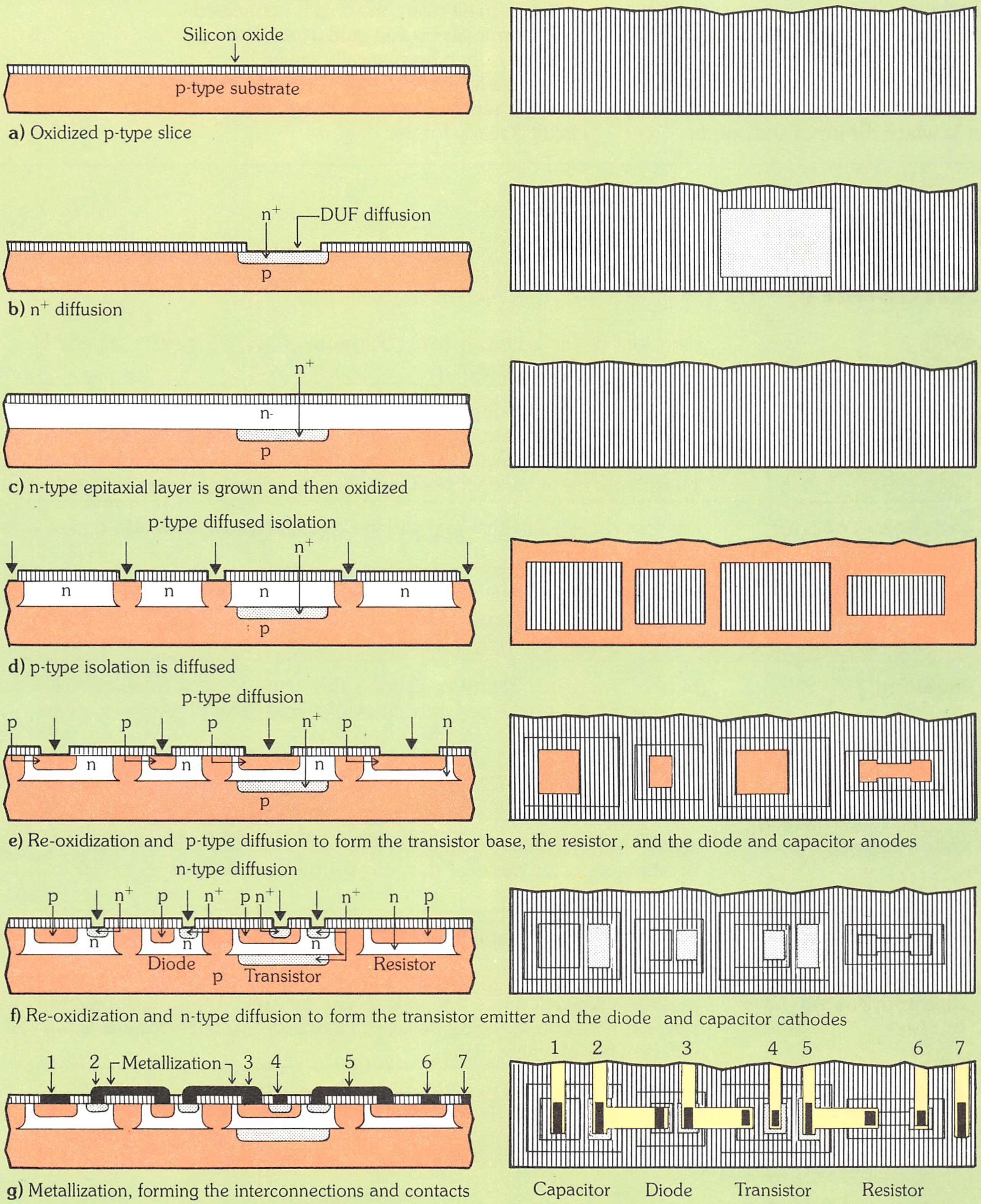
Testing, separation and packaging

Before packaging, each IC chip is tested to ensure that it functions correctly. This is done by a computer controlled machine which rapidly checks one circuit after another, marking faulty chips with a dab of ink. Electrical connection with the test circuit is made with very fine needle-like probes, which are rapidly placed on each chip with considerable precision.

The individual chips are then sepa-

13

Side and plan views showing the stages of IC manufacture



a) Oxidized p-type slice

b) n^+ diffusion

c) n-type epitaxial layer is grown and then oxidized

d) p-type isolation is diffused

e) Re-oxidization and p-type diffusion to form the transistor base, the resistor, and the diode and capacitor anodes

f) Re-oxidization and n-type diffusion to form the transistor emitter and the diode and capacitor cathodes

g) Metallization, forming the interconnections and contacts

rated from each other by a diamond tipped cutter; rejected chips are discarded, the remainder being assembled into **packages**. The purpose of the package is to house the tiny chip and connect it to the outside world via connecting wires or pins. Various types of packages are available, the most widely used being containers of the plastic or ceramic dual-in-line (DIL) type, in which the input and output connections are made through metal legs projecting from the plastic or ceramic body, in two rows; other examples include the flat package and the plastic chip carrier package. In all cases, the chip is connected to the terminals by thin gold wires. The package is then hermetically sealed by fixing on a lid, or encasing it in plastic. After a further series of tests, the integrated circuit is ready for use.

Glossary

DUF	diffusion under epitaxial film. Diffusion of an n^+ region, needed to make integrated transistors
epitaxial growth	method by which a doped silicon layer is grown on a substrate with continuous crystal lattice structure. The substrate is heated and exposed to hydrogen or silicon chloride to provide the growth, and phosphene (n) or boronethane (p) to give the doping
junction capacitor	integrated capacitor that exploits the capacitance of a reverse-biased p-n junction
junction isolation	p-n junction between each integrated component and the p-type substrate. Conventional current cannot pass from n to p, so each component is electrically isolated
masking	part of the planar diffusion process that uses a mask to selectively expose areas of photoresist to ultraviolet light. The unexposed areas can be removed and then diffused
MOS capacitor	integrated capacitor made from a basic metal-insulator-semiconductor structure
oxide isolation	system that electrically isolates an IC's components, by forming islands of semiconductor material that are surrounded by a layer of silicon oxide
photoresist	light sensitive material that hardens when exposed to ultraviolet (UV) light
planar diffusion process	p and n-type dopants are selectively diffused into the substrate, through windows in the oxide layer, creating components made up of different p and n-type planes
solid state diffusion	otherwise known as the diffusion method. The process that diffuses different dopants into a semiconductor substrate